DER PRÜFINGENIEUR

The Journal of the German Federal Association of Design Review Engineers

www.bvpi.de | ISSN 1430-9084

Special Edition 2020

Dear friends and colleagues,

The integrity of buildings and civil engineering structures is an integral part of public safety and society relies on it. To ensure structural integrity, methods must be applied to eradicate human errors from structural design. The common thought, that safety factors, defined in design codes, also account for human error, is incorrect – the massive consequence caused by human errors cannot be included in these factors. The only way, that has proven effective in common practice, is independent design review. The importance of design review is well-known and consequently, most countries have a system for design review in place. However, the way the design review is performed differs from country to country.

The design review by an technically and economically independent and chartered design review engineer in combination with a strong building authority, that regulates the requirements for building products, has proven to be an appropriate approach. It has been used and established in Germany for over a century.

Due to the ongoing Pan-European harmonisation of standards and the corresponding regulations for construction products, as well as globalisation effects in general, the established design review regimes are put under the microscope, worldwide. Since these systems represent a major part of a country's "construction identity", changes will not happen without friction. Ideally, an open discussion, led by unbiased thinking about the safety of our structures, will provide means for a design review system, which fits well into a country's construction practice, but is also open for discussion, optimisation and enhancement to protect society from harm due to structural collapse in the best possible way.

In recent years, the German Bundesvereinigung der Prüfingenieure für Bautechnik (BVPI) – Federal Association of Design Review Engineers – has developed an international approach, which is laid out in depth in issue 57 of the Association's semi-annual journal Der Prüfingenieur. To allow for improved communication about human error within the community of structural engineers and to present our system of independent chartered experts, who do not only perform a design check and site inspection but also provide valuable insights at earlier design stages, beyond the palpable horizon, we contributed to international conferences and journals. This special edition of the journal Der Prüfingenieur summarises these efforts and provides the contributions in their original format.

We are looking forward to a growing discussion about human error and how to tackle it to achieve reliable and safe structures. But most of all, we wish you an interesting read!

Robert Hertle

Eric Brehm

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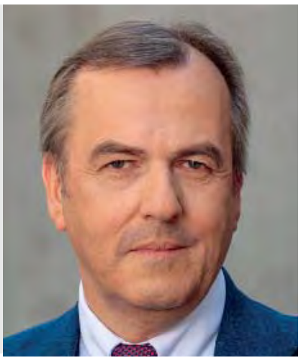

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CONTENT

Titelfoto: Robert Hertle

Design Review – The Necessity to go International

In order to shape and secure the future of our profession as design review engineers, it is indisputably necessary to take part in European standardisation effort. This not only requires influencing the so-called code writers, but also a better understanding of the global dynamics of standardisation. Europe must be careful not to be marginalised between the concentrated standardisation strategies of the United States and China. Both try to use their standards as a means of gaining economic influence. If we are not able to establish the European standards as a global, undisputed benchmark in the civil engineering community, there is a real danger that future projects will be dominated by standards and thus by design philosophies from abroad. In this case, not only the quality provided by the European standards but also our profession are at stake. Therefore, internationalisation is an imperative for the future policy of our association.

by Prof. Dr.-Ing. Robert Hertle
Prof. Dr.-Ing. Eric Brehm
Dr.-Ing. Markus Wetzel

1 Where We Stand

About a decade ago the Pan-European-Project to harmonise the structural engineering design standards and to propagate the free market for construction products, which was started about 45 years ago, entered a new phase. This phase was characterised by the following:

- Transformation of the first-generation Eurocodes from Pre-Standards to full EN-Standards with the condition that national standards shall not contradict the rules and regulations of the Eurocodes.
- Compulsory implementation of the European Construction Product Regulation – CPR – with the consequence that no nationally amended requirements to construction products defined by harmonised European Standards are allowed.
- Attempt to integrate national design traditions into a common European design philosophy.
- Globalisation of Standardisation as means for propelling economic interests.

The publication and implementation of the structural Eurocodes led to intensive and fierce discussions between the code-writing fraction and the rest of the civil-engineering community. The central insight of these discussions was that the overwhelming majority of these structural engineers disregarded the momentum of the European development since the 1990s crucially. Due to the German peculiarity of the official implementation of standards by the building authority, the day-to-day work of structural engineers in Germany was affected by the publication and implementation of these codes momentarily and deeper than in every other European country.

In January 2011 this experience triggered the formation of PRB in Germany, the Initiative for Improving the Practicability of the Rules for Building-Constructions, by engineering associations, scientific organisations and the building industry. The main purpose of PRB is to enable the development of a concise set of technical rules and regulations which mirrors the state-of-the-art knowledge, i.e. to provide safe, easy to use and unambiguous rules by defining the scope of the standardisation work and by providing reasonable proposals for the enhancement of the Eurocodes.

During the work in PRB another experience evolved: The fundamental misunderstanding of the importance of standards throughout Europe. This, combined with the inevitable inertia of standardisation procedures, led, after the first years of enthusiasm to widespread disappointment within PRB and its supporters. The PRB workshop on the Ease of Use of the Eurocodes [1] held in Berlin in December 2014 highlighted the differences between the German understanding of the quality of the Eurocodes and the understanding of the other participating nations in brightest colours. As mentioned above and following the German standardisation tradition, standards which are implemented officially by the German building authority develop a nearly legal standing, whereas in almost all other European countries standards are an important source of knowledge but not the only one. Consequently, the vast majority of the countries participating in the Eurocode-programme understands the outcome of the year-long, compromise driven standardisation effort as a "model-code" instead of a piece of paper which develops an almost legal quality. Remarkably, the basic rational for the Eurocode-programme state that the application of the Eurocodes in the participating countries is voluntary. The only condition laid out there is, as already mentioned, that there are no contradictory rules published or valid. Or, as the majority of the speakers at the PRB-Workshop stated, the Eurocodes are a powerful tool to amend existing national regulations where these have deficits or where there is a lack of information, but none of them supported the idea that with the publication of the Eurocodes existing national rules and regulations for structural engineering should be completely withdrawn. Thus, the question must be put on the table, whose understanding of the quality of the Eurocodes is the reasonable one?

Having this attitude towards the character of the Eurocodes of the majority of the CEN-member states in mind, it is not surprising, that the PRB effort to facilitate the use of the Eurocodes and to streamline the common standard into a more user-friendly format faces enormous obstacles. Consequently, this led to the situation that PRB had to review its central objective: Is it furthermore possible to follow the basic claim of enhancing the Eurocodes and make them fit for an easy use or does Germany have to reconsider her standardisation approach in a way that is compatible to the European philosophy?

Looking at the interim results of the Eurocode effort for the standards' third generation, which is deemed to be published by the end of the decade, Germany has to realise that she is standing at cross-roads. One direction points to the contrary of PRB's original aim, to the implementation of standards which are more complex and less suitable for the day-to-day use, the other leads the way to a modern understanding of technical rules and regulations, which differs significantly from the traditional German approach.

The retrospect on more than forty years of European standardisation history allows only one answer to the above posed question: Germany has to accept, that the future lies in modern, model-code type standards which cannot be implemented by the building authority in a way as it was done for the last century. It will be the task of the building authority, and this is an enormous one, to distil the information written down in the European Standards in a way that the basic duty the building authority has to fulfil, to protect the people from undue harm as it is stated in Germany's Basic Law, is covered. This can only be done by the publication and implementation of concise documents which address the crucial questions of structural engineering and which allow the use of the Eurocodes as well as the use of other secondary sources, like the complementary publication of technical and academic associations.

For Germany this will be a considerable leap in the direction of liberalisation within structural engineering as this step inevitably leads to the relinquishment of today's comfortable design environment in which the feeling predominates that almost everything is regulated by the building authority and is therefore indisputable. But as it always is in changing times, this will be the chance for design review engineers to claim more responsibility and to strengthen their standing and position within the society. Liberalisation of the set of technical rules and regulations goes only well, if the supervision bodies are strong and above all independent of any interests to make sure that liberalisation is not a one-way path.

The complexity which goes along with liberalisation efforts lies on our desks every day when we reason about the problems related to the safe and successful use of construction products within the remit of the CPR. The expertise statement written on our behalf by Udo Di Fabio [2] elucidates the problem perfectly. The quintessence of this deliberation is, only with a strong and independent design review, i.e. the design review engineer acting as part of the public administration, the European liberalisation efforts, which are solely driven by the wish of removing trade barriers, can be brought in line with the states' responsibility of protecting its people. Udo Di Fabio's arguments for a responsible handling of the CPR give us the blueprint for the debate on how to adopt a new regime of harmonised European design standards and they show that design review of building constructions is one of the original tasks of a state's government, which can only be properly addressed by devolving this to trusted, independent experts.

Summarising these two traces of development, i.e. the formulation of a commonly accepted European standardisation philosophy and the fencing of the negative side-effects of liberalisation, both offer new opportunities for a truly independent design review which is mandatory to provide the safety the society deserves and is entitled to. Facing these challenges leads consequently to the acceptance of opening up our traditional way of performing structural design and design review and trying to merge the different design philosophies of the European countries to one European design approach. This will need time, endurance and the will to be an active player in this game.

One remarkable episode in this context was and is the discussion dealing with Annex B of EN 1990 [3]. A modification of this Annex was proposed by the Norwegian delegate to CEN/TC 250, the technical committee of CEN in charge of the structural Eurocodes. The aim of the modification was to standardise different levels of design review spanning from self-check via in-house-check in a design office to independent design review. Beside the question whether a European standard is entitled to assign responsibilities – this is, based on the European Treaties, the sole right of the nations within their jurisdiction – this modification of EN 1990 Annex B addressed the question of the quality and independence of the design review and therefore this advance impaired our profession directly. A common effort of the German delegates in the respective committees, i.e. our colleagues on all stages – CEN-committees and working groups, direct discussions with the involved parties, political influence via the German building authorities, etc. –, led to success. The proposed standardisation of the design review was abandoned. At a later date, discussions with international colleagues in charge of building safety showed that they are by a vast majority, in favour of an independent design review instead of self-check or in-house-check schemes. Reasoning about the origins of the above mentioned proposal and digesting the endless discussions it becme pretty obvious that it was mainly propelled by personal interest and not the outcome of a broad national consensus.

The discrepancy of personal and national interest was obvious in other instances, too, supported by the organisation and division of European

IN BEIJING, CHINAS CAPITAL, representatives of the Bundesvereinigung der Prüfingenieure für Bautechnik (BVPI), Dr.-Ing. Markus Wetzel (l) and Prof. Dr.-Ing. Robert Hertle (r), and the president oft the Deutsches Institut für Bautechnik, Dipl.-Ing. Gerhard Breitschaft, accompanied by his colleague Dr.-Ing. Doris Kirchner, Head of Section-Corporate Communications, International Relations, explained in 2019 the principles of German building control and its embedment into the European standardisation architecture.

standardisation into Scientific Committees (SC) and Working Groups (WG), where national delegations convey the national consensus defined in the national mirror committees, and the Project Teams (PT), where the actual work on the code manuscript is performed by independent experts, who competed in a tender and receive compensation. The group of possible experts for a PT is small. Consequently, a member of a SC may also be an expert in the PT. It has happened several times that such a member has argued heavily contrasting opinions in the SC, where the member is bound to national consensus, and the PT, where he can act as an independent expert, only bound to his personal interests.

Generally it has to be stated that standardistion is primarily driven by minority interests, i.e. interests of groups or persons an not by concise national standardisation strategies, hidden behind the European curtain. This curtain allows the code-writers to avoid stern discussions about their work, as typically upcoming discussions are terminated by the reference to the European decision making process, or to put it in other words: In Germany often the argument that the Europan standards are dominated by the big British engineering companies is stressed and, travelling to the UK and asking the identical question you will hear that there was no other solution possible due to the overpowering influence of the German Professors. The simple reality is, the standards are dominicated by personal interests and personal engagement.

To shape and safeguard the future of our profession, it is indisputably necessary to take part in the European standardisation effort. Not only to influence the code-writing community, but also for a better understanding of the global momentum of standardisation. Europe must be cautious about not being marginalised between the concentrated standardisation strategies of the United States and China. Both try to use their standards as means for gaining economic influence. Especially China hardly hides her ambition in this respect. If we are not willing to establish the European standards as a global, non-disputable benchmark in the community of structural engineers, the possibility that future projects will be dominated by standards and hence design philosophies from abroad is obvious. In this case, not only the quality provided by the European standards but also our profession is at risk. So, going international is one imperative for the future policy of our association.

2 The Path from German Boroughs to International Recognition

The discussion about the modification of Annex B of EN 1990 and the international debate on how design review should be performed led in 2016 to the decision to present and explain our position on this issue on the 19th Congress of the International Association of Bridge and Structural Engineering – IABSE – "Challenges in Design and Construction of an Innovative and Sustainable Built Environment" in Stockholm. Both papers submitted to the scientific committee were accepted and presented during the session "Bridge Risk Management". The more general deliberation of the German design review process "An Empirically Verified System for Quality and Risk Management" [4] and the explanatory contribution "Checking of Structural Safety – Experiences with Large-Scale Structures" [5] were received well in the auditorium and triggered partly lively discussions on the is-

Foto: reddit

THE GRENFELL TOWER FIRE on July 14th 2017 prompted the colleagues of the British Ministry of Housing, Communities & Local Government to contact the Bundesvereinigung der Prüfingenieure für Bautechnik to get information on how building safety is organized in Germany.

sue. Beside the technical exchange of opinions, at this event important personal contacts to colleagues from the United Kingdom and from the United States were developed. Within short time we were invited to take part in international boards: CROSS – Confidential Report on Structural Safety –, a joint committee of the Institution of Structural Engineers IStructE and the Institution of Civil Engineers ICE in London, and IABSE Task Group 5.1 on Forensic Structural Engineering.

In the following year we took the chance to present our design review philosophy at the IABSE Workshop "Safety, Failures and Robustness of Large Structures" in Helsinki with a paper on "Influence of Human Error on Structural Reliability" [6], in which methods of tackling human error we explained and discussed via several examples from the day-to-day work and on the IABSE Symposium "Engineering the Future" in Vancouver delivering a lecture on "Influences on Determining Structural Reliability" [7]. A major topic of these contributions was deliberating the question whether human error can be tackled by applying bespoken safety factors when designing a structure. The examples presented showed that this is not possible in structural engineering as the prototype character of building constructions excludes the successful application of RMS-strategies – Reliability Management Systems – well known from industrial and serial production. The only reliable method to prevent severe accidents caused by human error is an independent design review process. All these activities were overshadowed by the Grenfell-Tower fire on June 14th and the following investigations [8,9]. The association was contacted in this context by our British colleagues, the above-mentioned institutions IStructE and ICE as well as directly from the British Ministry of Housing, Communities & Local Government, to give inside information how building safety is organised in Germany.

The year 2018 was dominated by two major incidents, the tragic failure of the footbridge at the Florida International University in Miami in March [10,11] and the near-miss failure of the Opal Tower in Sydney in late December [12]. Both drew the attention to the question of preventing failures due to human error. In the respective expertise statements [11,12] emphasis is laid especially on a proper and independent design review, which was missing in both cases. The colleagues from the US National Transportation Safety Board – NTSB – in charge of the investigation of the Miami footbridge collapse came up with a dramatic finding:

Although the design reviewer recognized that he should have examined the nodes and stages, he indicated that there was not enough budget or time to evaluate those factors. Contributing to this review failure was the reviewing firm's lack of qualification to do the work. Further, no specific guidelines call for nodes or construction stages to be included in independent bridge design reviews. The NTSB recommends changes to bridge design review procedures to ensure that bridge nodes and construction stages are included in independent design reviews.

Comparable statements can be read in the report analysing the reasons of the Opal Tower incident. This background paved the path for our attendance at the IABSE Symposium "Tomorrow's Megastructures" in Nantes and at the 5th fib International Congress "Better-Smarter-Stronger" in Melbourne. On both of these occasions, we stressed again our position that human error can only be prevented successfully by using independent design review procedures with the papers "Influence of the Design Review Process on the Structural Design Engineer due to Human Factors" [13,14], "Checking of Structural Safety – Experiences with Large Scale Structures" [15], a revised and expanded version of the paper presented in Stockholm. As it was to be expected, our arguments were partly challenged on the open stage, especially when we introduced our proposal of a collaborative design review scheme, but the following invitation to give a lecture on the German design review principles titled "Independent review of structural documents and on-site-inspection by Prüfingenieure für Bautechnik" at the October 2018 IRCC – Inter-Jurisdictional Regulatory Collaboration Committee – Workshop "Building Quality – Improving the Compliance to Building Regulations" in The Hague [16] showed us that our activities to make our profession recognisable in Europe and beyond started to become successful.

In 2019 we achieved to become an affiliate member to IRCC – an organisation gathering building supervision authorities which have a status as standard-setting entities – supporting the Deutsches Institut für Bautechnik – DIBt – as the German main delegate. During the IRCC sessions in Beijing and Las Vegas a lot of bi- and multilateral conversations on independent design review took place. Countries like Sweden, Norway, Singapore and the USA showed real interest in understanding our way, partly because they have technical and/or economic problems with their existing procedures, partly because they have abandoned independent design review following the political mainstream of the 1980s and 1990s and are now facing severe problems with safeguarding the expected building quality and safety. The talks with Australia and the UK have already reached a further stage: We were invited to explain the German design review scheme and the approval procedures for design review engineers at the respective governmental bodies, the British Ministry of Housing, Communities & Local Government in London and the Australian Building Codes Board in Canberra. The first mentioned meeting took place in November 2019 in London, the second was scheduled for March 2020 in Australia but due to the SARS-CoV-2 outbreak postponed and provisionally replaced by a Video-Conference in May 2020.

On the international conference stage 2019 was dominated by the IABSE Congress "The Evolving Metropolis: Addressing Structural Affordability, Durability, and Safety" in New York City. Besides the presentation of two papers "Challenges towards Design Review due to Cultural and Human Factors" [17] and "Practical Examples of Successful Design Review" [18] which dealt again with the problem of addressing the consequences of human error and the importance of technically as well as economically independent design review schemes and which were the outcome of an Anglo-German co-operation, the IABSE Task Group 5.1 on Forensic Structural Engineering resumed, after a change of command, its work. We, as the German delegates took over the task to edit a special edition of IABSE's quarterly journal Structural Engineering International – SEI – dealing with forensic engineering and pre-emptive design review strategies based on forensic findings. The discussions which evolved in the wake of our talks were characterised by a great openness towards our arguments, as quality problems of building construction continued to surge in the past years.

These activities were framed by the publication of two papers in SEI in 2017 and 2020 [19,20]. The main topic of the first, in 2016 submitted contribution "Failure Identification: Procedural Causes and Corresponding Responsibilities" was to emphasise the necessity and the benefits of forensic engineering strategies for the enhancement of structural engineering. The investigation and the systematic deliberation of root causes of structural failures, near misses and design-, as well as execution-flaws provide the essential inside-information, i.e. the lessons to be learned which establish the indispensable knowledge base for elaborating methods and procedures to avoid them in the future. The second paper "Design Review as a Powerful Tool to ddress Human Factors: A Collaborative Approach", an invited contribution for the SEI-special edition "Best of Nantes", published on the occasion of the 2018 IABSE Symposium "Tomorrow's Megastructures", focuses on investigating the interaction between the designer and the design review engineer when working together on ambitious projects as a team and with the clear cut task to tackle human errors. Especially the non-technical, i.e. the psychological aspects of this co-operation are addressed, as the root causes for human errors and are found predominantly beyond purely technical issues.

Looking back at the journey of going international out of the confinement of the German boroughs, which started four years ago, we can state that the Bundesvereinigung der Prüfingenieure für Bautechnik got an international profile and is acknowledged as an experienced partner and advisor in all questions concerning building safety and independent design review – structural as well fire-protection –. Due to the development of increasing numbers of severe structural failures and innumerable near misses and the root causes in mind, this step into internationalisation provides the chance that the German design review process will be developed into a widely accepted blueprint for building supervision authorities.

3 A New Definition of Standardisation

One of the core issues of the structural engineering community is the development of robust, reliable and, as much as possible, unambiguous and commonly accepted rules and regulations for the design and assessment of civil engineering structures, based on knowledge and experience. The summary of all this information is usually known to all of us as "standards". As knowledge and experience are closely linked to design-tradition and design-philosophy, it is obvious that the out come of this process, i.e. the standards, mirror the specific characteristics of each society.

Having this in mind and aiming at a truly international framework for structural engineering standards, the process of standardisation, as it is known to us and to all other societies, has to be reconsidered. To succeed with the mentioned task, it is imperative to integrate the traditions and philosophies of all involved parties instead of trying to perpetuate the things as they were done throughout the past decades on a national level.

The actual generation of the structural Eurocodes suffers in this respect, as the standards are written to please all the different national standardisation approaches of the participating countries. This outcome of the typical consensus-seeking behaviour of the European code-writing fraction has severe side-effects due to the already explained deficits with respect to a truly common understanding of the purpose of standardisation throughout Europe.

Thus, the modern design environment and the adaption of this in the set of technical rules and regulations require a completely new approach. Even if it is not an easy task to leave the familiar surroundings, i.e. the way the standards of the past were written, it is inevitable to do this, as the modern design tools require a corresponding technical framework.

The term framework is chosen intentionally and is the result of reasoning about the manifold contradictions between modern, IT-based design tools and the content as well as the lay-out of the actual standards which is deeply rooted in the pocket-calculator-past. Both, the extensive possibilities provided by the modern design tools and the earlier mentioned necessity of integrating century-old design philosophies into one coherent way of doing demand to withstand the temptation of the past to regulate the last "nut and bolt".

This framework must enable:
i) The definition of all the essential elements indispensable for a safe structural design, i.e. the fundamental safety concept, the basic requirements the materials have to comply to, the actions and the methods suitable for performing the structural design.
ii) The use of model-code-type information as well as the use of secondary information for the structural design in the day to day work.

Looking at these requirements, a hierarchic standardisation structure seems to fit best. This would allow the flexibility needed in the modern design environment to incorporate state-of-the art methods into the generally accepted process defined by the standards. Based on mandatory standards – documents like the ones described in i) – complementary rules and regulations according to ii) may be used as long as the principles laid out there do not contradict with the provisions of the mandatory standards. Besides adopting the requirements of the modern design environment, a structure like the one explained, will also enable the integration of different design philosophies into one coherent standardisation concept.

Another positive side-effect resulting from this scheme is that it would go perfectly along with the politically pursued, tired education principles in engineering sciences which result in considerably different knowledge and expertise levels of the university graduates. Depending on the knowledge and the level of education, distinctive design tools can be made available, spanning from the pure, fundamental formulation of the basic design principles deemed for the experienced, knowledgeable engineer to text-book-like publications for an easy handling.

However, standardising the future of structural engineering reaches far beyond the technical horizon, it also has to reflect the political and social aspects influencing our profession. These aspects, often neglected by engineers because they usually are of an easy to understand, non-technical, weak and since deeply emotional character, get more and more important in a globalised environment where academic expertise is of secondary or tertiary importance for the political decision bodies on which we have to rely on when trying to enhance our profession and its standing within the society. Therefore, we must address these issues with the same determination as we are used to exhibit when involved in the elaboration of the technical content of our standards. Only then, we will succeed in pursuing our utmost mission to successfully pave the road for the modern design review. Additionally, while doing this, we will be in a position which allows us, preceding to the actual technical work on the documents, to define basic principles and requirements essential for the future generation of structural design standards at a pivotal point.

Summarising the situation at hand, standardisation has evolved during the last decades into a complex endeavour which requires as much psychological and political skills as technical experience and knowledge. To succeed, we have to face this challenge and we have to accept, that the romantic idea of standardisation, clear-cut technical solutions and nothing else, most of us, particularly the authors, have in mind, belongs to the past and that the European standardisation effort has to be defined anew to fulfil the expectation, especially concerning quality, coherence, presentation, user-friendliness and international reputation, the community of structural engineers puts into.

4 The Benefits of Collaboration

Increasing complexity, technically as well as politically, usually goes along with the necessity of sharing the burden and identifying personal capability and common vigour. Teamwork needs to be "teams at work" instead of "I team, and you work". Going international was only possible, after vanquishing reservations driven by the well-known romanticisation of good old times in which the horizon was palpable, through a joint effort of colleagues within and outside our association. It required, in a true sense of collaboration and mutual support, the association's determination, the respective long-term perspective, and the willingness of the colleagues abroad to listen to our arguments and to discuss them open-mindedly and based on indisputable facts. These were the essential ingredients for the more than positive reception we experienced on the international stage, after years of doubts and innumerable discussions, many within our association.

Out of this atmosphere, mutual international collaborations evolved which led to some crucial perceptions:

- Structural engineering reaches far beyond the pure technical issue of verifying the strength and/or serviceability of single components, building-kits or structures as a whole. It has to face the respective political and societal problems with the same scrutiny. Only when we accept this as an essential part of our profession, we will be in a position to shape the future instead of reacting and trailing behind.
- The community of structural engineers around the world is searching for answers on almost identical questions arising from the often accidental and unpredictable amalgamation of technical, educational, and social developments.
- The liberalisation efforts of the governments and public administrations dating back to the 1980s and 1990s are increasingly questioned around the globe. Independent expertise is more and more esteemed as a value itself and as an indispensable part of the public administration´s responsibility.
- Opposite to the widespread opinion in academic circles that sophisticated analytical reliability analysis methods and safety factors derived from these studies will be the tool of choice, worldwide forensic studies of structural failures and near misses gave convincing evidence that human error can be tackled successfully only by implementing compulsory independent design review schemes.
- The advanced German independent design review scheme with its century old tradition is regarded as a role model for implementing comparable "second opinion" procedures in the jurisdictions around the world.
- Last but not least, going abroad and being challenged in one´s opinion by colleagues with distinctive different backgrounds opens up


Foto: NTSB

IN MARCH 2018, the pedestrian bridge spanning over SW 8th Street in Miami collapsed during erection due to node-point failure onto the heavily occupied road underneath.

another view on our profession and our way of working. Integration of these experiences into our association´s decision process when reasoning about future activities and developments is without any alternative.

Especially the view on our day-to-day work from abroad and the various arguments with our colleagues from around the world on how to perform the design review successful and efficient led to the necessity of a re-adjustment of our decade-old German self-conception. Design review in the modern design environment has to keep up pace with the societal and technological developments and it has to prove its efficiency – both technologically and economically – at all stages of a project. To cope with this, in itself simple insight, it is necessary to leave the traditional way of checking the structural calculations and the design drawings with a headmaster's attitude after they were submitted for the review.

Instead design review has to be understood as an integral and essential part of the quality control scheme of the design of a structure, the execution on the building site and the whole processchain, i.e. as a catalyst to improve the design for the benefit of all participating par- ties by addressing the often friction-prone interfaces of the involved entities directly and independently via the design review process. To achieve this, it is important to get in touch with the project as early as possible. Good collaboration between the designer and the design review engineer utilises the potential of a technically and economically independent expert to derive, if possible, a better and more effective design and provides benefits for all parties involved by creating a less error-prone design environment.

Beside the considerable benefits of collaboration when working on tangible projects, on the international stage the collaboration between our colleagues from building authorities, supervision bodies and standardisation organisations and us was, as explained earlier, fruitful for all parties involved. Our common interest, the similarity of the experiences gained during the day-to-day work when assessing submitted structural design documents and/or inspecting building-sites, the social and political challenges to overcome when trying to adjust methods from the past and to make them fit for the future and the necessity to emphasis and explain the peculiarities of the prototype-industry "building-construction" to legislation bodies which hardly recognise the necessity to deal with this distinction, i.e. between a serialised-product like a switch and a bespoken building or structure, responsibly and which are susceptible to easy to digest marketing arguments instead of reasoning about the more complex stuff of technical interdependencies, helped enormously to deliver our arguments at the relevant institutions, especially as international cross-references usually open doors at all levels which are kept shut when doing it with a local or national background.

5 The (Inter-)National Perspective

Keeping and enhancing the national status and gaining international recognition for our profession needs the long view, persistence, resilience and endurance. Looking into the rear-view mirror shows that a lot was achieved during the last four years. Out of the confinement of the German boroughs our association gained, by a common and unflagging effort, international reputation. Our advice and our expertise are sought after by colleagues from building authorities, approval and supervision bodies and standardisation organisations on four continents. But it is not the recognition we were looking for, it is the common spirit of the international community of structural and fire protection design review and the profound understanding of the responsibility for the safety of the built environment, handed over to us as trustees for the society, that really matters. Thus, the national and the international perspective amalgamate to one, delivering the society structures that are safe and usable for the deemed purpose.

This aim cannot be reached on a purely national base. European cooperation is imperative to establish the standards we are accustomed to as the reliable benchmark in a globalised world and to safeguard what was achieved throughout the last century, otherwise we will wake up one day with standards and technical rules and regulations to comply to written far beyond our premises and without any European influence. So, what is to do, to keep our flag flying? The journey we embarked more than four years ago, taught us the following lessons:

- Politics matter, even if we may not like it. The future of our profession, i.e. the design review engineers – structural as well as fire protection –, will not be shaped by more or less sophisticated technical rules and regulations, it will be shaped by politics.
- Facts matter, even if they are laborious to establish, or, as Hans Rosling explains it in his remarkable book Factfulness [21]:
A fact-based world view is more comfortable. It creates less stress and hopelessness than the dramatic worldview, simply because the dramatic one is so negative and terrifying.
So, understanding what is really going on is only possible when we gather all the necessary information – technical, societal and political –, in a globalised world by active participation on all the mentioned levels. The limitation to the technical aspects only, what we engineers are usually accustomed to, blocks the view on the broader picture and may lead us into the wrong direction.
- As politics usually follow rules significantly different from the sober engineering understanding, we have to adapt our association´s strategy for propelling our profession accordingly.
- Common to all political developments is that they follow currents which do not stop at a country´s border, hence the future of our profession is moulded successfully only by joining forces with design review engineers, supervision bodies and building authorities around the world.
- The worldwide attention on fire protection issues in the aftermath of the Grenfell Tower fire in 2017 showed that design review has to be understood as an integrated task of structural and fire protection design review engineers. Especially the "fire-threat", palpable to everybody, made the politicians susceptible for our arguments.
- Understanding the intentions of the United States and China correctly, Europe has to develop state-of-the-art technical rules and regulations which define the benchmark no structural design can ignore. If she fails here, the future of our technical rules and regulations will lay far beyond our sphere of influence.
- To succeed, we have to abandon the traditional, nation-centred standardisation mechanisms and have to open up our mind to modern, model-code type standards which work as master documents and allowing the integration of different traditions and design philosophies.

The authors are convinced that there is no alternative to the international route taken. Only when the engineers responsible for the safety and the structural integrity of building constructions, i.e. the design review engineers – structural and fire protection – launch a focussed, supra-national, effort for improving the design environment the necessary impact on the political decision bodies can be developed to enable them to withstand the usually easy to digest economic arguments and to take the time to listen and to follow our thoughts in the interest of enhancing the safety of building constructions.

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Bautechnische Prüfung – Die Internationalisierung ist notwendig

Um die Zukunft unseres Berufsstands als Prüfingenieure zu gestalten und zu sichern, ist es unbestreitbar notwendig, sich an der europäischen Normungsarbeit zu beteiligen. Dazu ist nicht nur die Beeinflussung der sogenannten Code-Writer notwendig, sondern auch ein besseres Verständnis der globalen Dynamik der Normung. Europa muss sich davor hüten, zwischen den konzentrierten Normungsstrategien der Vereinigten Staaten und Chinas an den Rand gedrängt zu werden. Beide versuchen, ihre Normen als Hebel für ihren wirtschaftlichen Einfluss zu nutzen. Wenn wir nicht bereit sind, die europäischen Normen als einen globalen, unumstrittenen Maßstab in der Gemeinschaft der Bauingenieure zu etablieren, besteht die reelle Gefahr, dass zukünftige Projekte von Normen und damit von Entwurfsphilosophien aus dem Ausland dominiert werden. In diesem Fall stehen nicht nur die europäischen Qualitätsstandards, sondern auch unser Berufsstand auf dem Spiel. Daher ist die Internationalisierung ein Imperativ für die zukünftige Politik unserer Vereinigung.

An Empirically Verified System for Quality and Reliability Management

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Abstract

From experience with structural failures, one can see that human error, in design and execution, is the major cause for these incidents. However, human error is not covered by any approach to structural reliability. Therefore, a system for quality and risk management is required that accounts for human error. Such systems are mostly organized on a national level and exhibit significant differences.

This paper compares corresponding international approaches on how to handle human error and evaluates them.

A proposal for an adequate quality and risk management system covering human error will be presented. The proposal will be composed of the best parts of several available systems to provide an empirically verified, widely accepted approach.

Keywords: design checking, reliability, human error, structural integrity.

1 Introduction

The protection of human life and its physical integrity are fundamental human rights and consequently a crucial part of a nation's legal framework. Structural failure is a catastrophic event that may cause severe injuries and loss of human life as well as damages to surrounding structures and the environment. In case of infrastructure, the impact of structural failure on society and economy is especially significant. Thus, structural failure must be effectively prevented by suited means.

However, total safety corresponding to a complete absence of structural failures is impossible. To provide the utmost safety without making structures inefficient and unaffordable, different approaches for building control have been chosen by various countries. In this paper, the causes for structural failure and the existing approaches for the avoidance of structural failure during design and execution will be assessed and an optimized approach will be proposed.

2 Approaches to the Verification of Structural Integrity

In design, sufficient structural integrity is thought to be achieved through application of partial safety factors which are deemed to define the necessary distance of the design values of the actions and the design value of resistances. Safety factors are derived from prediction models and stochastic assessment, i.e. the design problem is formulated under uncertainty to account for variations in so-called (random) basic variables such as load magnitude, material strengths, geometrical deviations, uncertainty in the prediction models etc. From there, the reliability of a structural component can be determined by use of advanced algorithms (see [1] and [2] for details). Note, that reliability is a characteristic property of a member that can be compared to the target reliability which is given in design codes (e.g. in Europe EN 1990). From the reliability analyses, deterministic approaches to account for the reliability of structural members are derived, with the concept based on partial safety factors being the most widely used one. In other words, partial safety factors account for uncertainty related to exceeding actions and material as well as geometric structural properties falling below the reference levels. This explains why the number of structural failures due to extreme actions in combination with significant deficits in structural strengths is fairly low (see section 3). However, probabilistic models describe uncertainty under a set of pre-set conditions. Reasonable deviations from the nominal values applied in design are thought to be included in this uncertainty. Human errors, however, likely lead to entirely new conditions as these are not capable by the mentioned probabilistic models. Thus, the academic structural system "without errors" requires a totally different verification than the real-world structural system "with errors", i.e. the partial safety factors commonly applied in design do not account for human errors.

3 Causes for Structural Failures

Structural failures have been documented since the recording of events. In ancient times, structural failures were considered to be acts of god since the events were often disastrous and unforeseeable. Nowadays, structural analysis allows for scientific verification of the structural integrity. However, structural failures still occur. Researching the structural failures in the past shows that the causes can primarily be categorized by:

A Failures due to unforeseeably high actions or insufficient structural strength
B Failures due to human error

Cause A refers to structures with appropriate design according to the valid design standards and codes at the time of construction. Failure then occurred due to extremely high loads, that exceed the characteristic value of the actions according to the appropriate codes in conjunction with low material strength. Failure due to this cause is unlikely and normally covered by safety concepts (such as partial safety factors) as mentioned in section 2.

Cause B is responsible for failure in almost every case – failure does commonly include some kind of human error. Errors in the development of design guidelines and rules are excluded from the definition of human error here. Table 1 shows the typical causes for structural failures in a more detailed way. The table is based on the findings of [3]. In the corresponding analysis, only 6% of failures were found to be caused by unforeseeable events. The by far larger portion of failures are caused by human error that could have been prevented by proper measures.

Table 1 Causes and distribution of structural failures according to [3] (published in [4])

Cause of Failure	% of total damages
Ignorance, Carelessness	37%
Insufficient Knowledge	27%
Underestimation of Influences	14%
Forgetfulness and Mistakes	10%
Unjustified Relying on Others	6%
Objectively Unknown Situations and Influences	6%

Human error can occur at every stage of planning and construction, not only during design. Therefore, it has to be taken into account and avoided during design and execution as well as during service. According to [5], human error is divided almost evenly between design and construction phases. Additionally, the often referred to "calculation flaw" has proven to be only a minor reason for a serious design error.

Human errors of the types provided in Table 1 do not happen without a reason. The commonly mentioned reasons according to [8] are:

- Time pressure, too low engineering fees

- Pressure to minimize the costs of the structural to be built
- Insufficient coordination of the design
- Black-box-type use of design software
- Lack of detailing
- Large amount of new standards and design rules

It becomes clear that human error, and consequently structural failure, is caused to a large extend by systematic and cultural issues (pay grids, time pressure) and thus the prevention of structural failure must happen systematically, too. The two main causes for structural failure, as mentioned above, must be tackled efficiently. While the cause A – failure due to unforeseeably high actions or insufficient structural strength – can be counteracted by design concepts in structural codes, cause B – human error – requires an organisational set of measures, referred to as **Q**uality or **R**eliability **M**anagement **S**ystem (QMS or RMS). Possible QMS or RMS systems may be provided in design codes, such as EN 1990, Annex B. The presented set of measures mostly includes design supervision and site inspections, which have proven to be the only effective methods to identify and prevent human errors.

4 Quality/Reliability Management System

4.1 Quality or Reliability Management System?

Quality, in its common definition according to ISO 9000, is the degree of fulfilment of requirements. The definition of ISO 9000 is derived from and aims at pure organisational quality. The quality of a product itself cannot be evaluated on this basis. Structures, as well as other products whose failure is directly linked to harm human life, must fulfil hard or indispensable requirements entirely. The most important of these indispensable requirements is structural integrity. In other words: structural integrity is a binary issue, it is achieved or missed. "90% structural integrity" are simply impossible, besides the fact that a deficit in structural safety is generally and legally not acceptable. Nonetheless, the quality of a design must be assessable – otherwise every design would be equal. Therefore, the quality of design can only be defined by defining hierarchically subordinate soft or relative requirements such as serviceability, efficiency, sustainability, flexibility etc. The very nature of these relative quality requirements makes them completely independent from structural integrity.

In consequence, the definition of quality as it has been introduced by ISO 9000 is insufficient for structural engineering. The term "reliability management system" appears to be more appropriate to be used for structures and will therefore be used in this paper.

4.2 Required Elements of a Reliability Management System

4.2.1 Efficiency

The effort for reliability management must be adjusted to the task. As an example, it is clear that a nuclear power plant requires a more detailed supervision than a detached house. Therefore, a general requirement for an RMS is efficiency by means of adjustable requirements.

4.2.2 Failure consequences and complexity of the task

To achieve efficient progress in design, the required level of design checking and review must be related to the severity of the failure consequences and the complexity of a structure, i.e. structures with severe impact on society in the case of a structural failure (infrastructure, large number of possible fatalities etc.) as well as highly complex structures (shells etc.) require higher levels of checking and review than simple structures or structures which will not cause severe failure consequences.

4.2.3 Relevant levels of design checking and review and site inspections

Design checking and review and site inspections are very important since they tackle both the previously identified causes for structural failures (see section 3). By assuring that the design and execution have been performed according to the relevant design codes, the probability of failure due to unforeseeably high actions or insufficient structural strength can be minimized. Additionally, human error is being covered, too. In an RMS, the required level of design supervision and site inspections must be detailed. In general, both can happen on different levels:

1. Self-check

Plausibility checks of design are performed by the (design) engineer him- or herself, as every engineer does every day, e.g. by using a pencil and an eraser.

2. Internal review

The design is reviewed by another person within the same design organisation. The possible spectrum of this method can range from discussion with a colleague to a check procedure run by a specialized department. The effectiveness increases with the chosen procedures and the independence – technically as well as economically – of the reviewing body.

3. External review

The design and execution is reviewed by an especially assigned organisation which is completely independent from the design organisation. This is a very effective method due to the lack of shared interest between the design and review organisation.

4. External review by an independent, chartered expert

The effectiveness of the review increases with the qualification of the reviewer. In some nations, reviewers that had to undergo elaborate licensing examinations perform the design review by fulfilling the responsibilities of the public administration. These individuals provide different angles, insight and extensive experience and often cannot only support efficiently in eliminating errors, but also help improve the original design. This is considered to be the highest level of design review.

Site inspections are required to verify the correct transfer from the abstract design level to the actually built state. The inspections can be performed by different parties and at different stages comparable to the above mentioned ones.

4.2.4 Qualification of designer and design review engineer

Due to the varying complexity of structures, the required qualification of the design engineer plays a major role in providing high-quality design. Qualification of the design engineer is often understood as background in form of academic degrees and relevant experience. Additionally, the capacity of the organisational background in which the engineer acts may have an impact on the available qualification of the engineer. For example, an excellent engineer working alone on a large-scale project may be overwhelmed while a poor engineer will not necessarily succeed because of the support of a large engineering firm. There are many examples of small engineering firms which excel in large-scale projects due to the organisational efficiency while large companies may be slow in processing due to the organisational overhead and vice versa. A link of engineering qualification solely to the organisational size, processes and capacity is not purposeful and will not provide sufficient answers. Much more, qualification must be based and assessed on a three-dimensional level: personal, technical and organisational qualification. This is especially important when it comes to the qualification of the design review engineer. The design review must not only be understood as a search for errors and flaws – it also opens up the chance of an independent second opinion with a possibility of improvement and optimization of the design at hand.

4.2.5 Cultural change

As identified in section 3, human error does not necessarily occur without advance notice. There are reasons that make a significant error more likely. To minimize the probability of significant errors happening, the original reason, such as too low engineering fees or unseemly time pressure, should be addressed. It requires a cultural change in the way we work, the way we assign work the way we communicate and the way we interact with the society. For example, open and unregulated markets will often yield the cheapest contractor as the one winning the tender. To work profitably, the employees of the winning contractor will have to be more efficient and often simply faster than the other competitors. On basis of a more satisfying fee, the need for a faster design and execution can be reduced and lead to higher degree of diligence. In some countries, engineering fees are based on fee schedules (e.g. in Germany). These schedules are often undermined by thoughtless competitors in the market but still work as a reference. A cultural change is required where engineers maintain fee schedules and do not fall for price dumping.

4.3 Common Types of Reliability Management Systems

4.3.1 General

The avoidance of structural failure falls within the responsibility of the legislation of the respective nation. The state administrates this responsibility by granting building permits. The RMS is consequently linked to the building permit. Every nation has different legislation so that the reliability management systems exhibit minor or major differences. However, the RMS can be divided into two general types depending on the main approach to the avoidance of structural failures.

4.3.2 Repressive System

A typical version of a repressive system is explained by the example of the system applied in France. For the issuing of a building permit, the building authorities only check zoning aspects and the building master plan. Structural integrity is within the responsibility of the parties involved with the construction: architect, contractor, and owner who are legally obligated to build up to the relevant codes. However, fulfilment is not to be checked by the authorities. The parties are also legally obligated to take out insurance policies to cover risks associated with the construction.

The advantage of this system is the financial safety in case of failure and damages since the insurance will cover possible claims. However, disadvantages are substantial – reliability management does not happen to prevent failure in the first place and the structural cost increases significantly due to the cost of the insurance policies. Design reviewing and site inspections are only performed if an involved party specifically requires these, e.g. the insurance might grant better conditions for the owner if design reviewing is performed. Compared to the above identified causes for structural failure, the following must be stated:

Cause A (unforeseeably high actions or insufficient structural strength) and B (human error) are not necessarily covered since there is not a legal requirement to review the design before the building permit is granted. A building permit can be obtained without design and execution supervision. However, design and execution supervision often happens under private law.

4.3.3 Preventive System

Contrary to the repressive system, the preventive system tries to avoid structural failure in general by consequent design supervision, already before the permit is granted, and on-site inspections for checking the execution. A typical example for a preventive system is the system applied in Germany, presented in Figure 1. In this system, a full design review by a highly qualified and chartered design review engineer has to be performed and reported to the building authorities before the building permit is granted. During construction, the design review engineer is responsible for checking all the relevant design drawings as well as for performing sample inspections of the execution (e.g. reinforcement in situ). The disadvantages of this system lie within the possibly larger inertia in the design and execution phase as an additional, economically independent party is involved. But this additional player introduces advantages into the design and execution process as he provides the prevention of failures and cost-efficiency since additional insurance policies are not required. Compared to the identified causes for structural failure, the following must be stated:

The first and second cause are covered since there is a legal requirement to check the design before the building permit is granted. A building permit cannot be obtained without design and execution supervision.

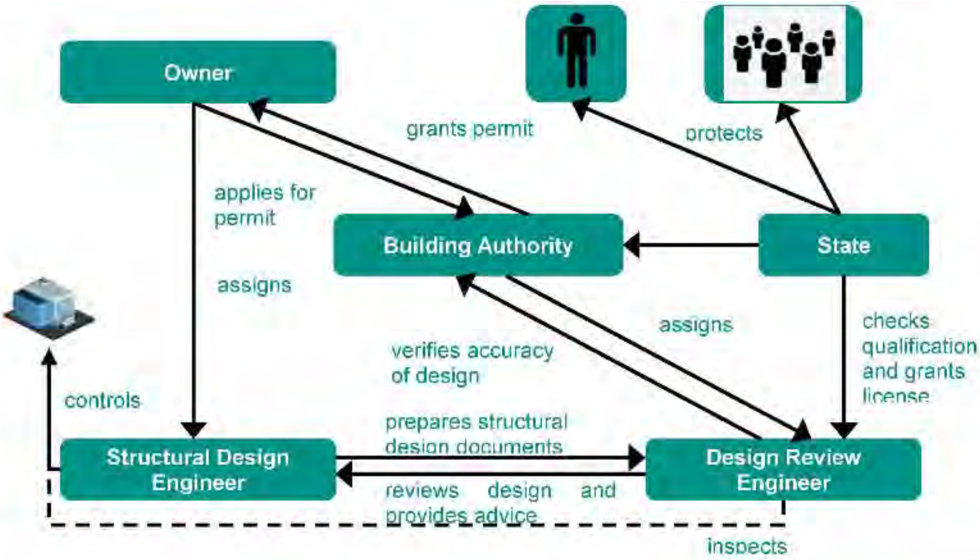

Figure 1 *Preventive reliability management system (example of Germany)*

5 Proposal for EN 1990, Annex B

5.1 General

In the (informative) Annex B to EN 1990, a certain quality management system is suggested. It is currently undergoing attempts for an enhancement with a new proposal being under discussion (see [8]) . This current proposal has led to an intensive perusal within the relevant CEN committees. The reasons for the discussion will be further explained in section 5.3. In the following paragraphs, the actual proposal will be briefly summarized and examined.

5.2 Content

The proposal is divided into two sections: design and execution. Its general idea is the classification of certain aspects related to design and execution and the subsequent derivation of necessary supervision measures. For this, several aspects are grouped into classes or levels which are then linked to the relevant levels of design and execution supervision. The following classes and levels were defined:

- Quality Management Classes

Quality Management Classes (QM) represent an overall measure for the ranking of quality management requirements defined by the following classes and levels.

- Consequence Classes

The consequences related to structural failure are categorized in 3 classes (CC), from less severe (CC1) to very severe (CC3).

- Reliability Classes

Reliability Classes (RC) are directly linked to the consequence classes. Each RC comes with a certain value for the target reliability of the considered structure.

- Design Quality Levels

Design Quality Levels (DQL) are supposed to assess and represent the capability of the design engineer with respect to the complexity of the task by a number of criteria. Also, the requirements for quality management measures within a company are supposed to define the possible achievable DQL. A range of possible criteria for the assessment of qualification is provided, ranging from “years of experience” to “computational capacity”.

- Design Supervision Levels

The different levels of design review (see 4.2.3) are grouped into three Design Supervision Levels (DSL) with increasing sophistication from DSL1, self-checking, to DSL3, external and independent design review.

- Execution Classes

Execution Classes (EXC) are related to the necessary execution quality specific to a project and are similar to DQL for executing companies or individuals.

- Inspection Levels

Inspection Levels (IL) are related to the necessary inspection levels specific to a project and are similar to DSL for executing companies or individuals.

5.3 Reasons for Controversies

The avoidance of structural failure and harm to the population is a strongly national responsibility. Thus, every nation has established its own procedures to safeguard the structural integrity of the built environment. Structural failures are very rare and consequently, the need for a novel organisation of a standardized RMS in a European code is not necessarily understandable. Additionally, a European attempt to influence this part of national legislation establishes a further intrusion into national sovereignty.

However, it must be made clear that the proposal has to be understood as an invitation for an NDP (Nationally Defined Parameter) within the system of the Eurocodes. It provides information – after all the annex is "informative" – on aspects that should be considered when assessing or enhancing existing Quality Management Systems applied in structural engineering. Note, that the system is referred to as "quality" management system due to formal reasons, as this term is used already in existing standards. Actually this term stirs controversies for the reasons explained in section 4.1 and the further use should be rethought as it is an irresolvable task to manage a binary system like the one explained with the indispensable requirement of structural integrity. Therefore, either when using QMS a clear distinction between the primary, i.e. indispensable quality feature and the subsequent relative ones is inevitable or the introduction of a more appropriate description of the necessary procedures to safeguard the structural integrity of the built environment is proposed.

6 A Proposal for an Empirically Verified Q+R Management System

6.1 Preventive System

As mentioned in section 4.3, a preventive system covers the identified causes for structural failure efficiently and should be preferred. This generally means that the building permit should be linked to design and execution supervision.

6.2 Proposed Classes

From the elaborations above the following classes should be introduced and applied consequently within an efficient RMS to cover the identified required elements from section 4.2.

- Consequence Classes (CC)

The consequences of failure must be used to determine the required effort for design and site supervision.

- Structural Classes (SC)

Complexity as a measure for error-proneness must be combined with the relevant consequence class. In Germany, structures are grouped into different structural classes in state law (see [9]). Also, the engineering fee from the national pay grid ([10]) depends on the complexity of the structure.

Table 2 Structural Classes according to [11]

SC	Level of difficulty	Characteristics and Examples
SC 3	Structures with high level of difficulty	• Complex statically indeterminate structures • Structures with non-trivial load scenarios and action effects • Highly complex structural systems requiring e.g. non-linear calculations or dynamic effects to be considered • Complex structures requiring new design techniques or design assisted by testing • Pre-stressed and post-tensioned structures

		• Difficult stability considerations required
SC 2	Structures with medium level of difficulty	• Difficult statically determinate or • statically indeterminate regular structures built with common construction techniques
SC 1	Structures with low level of difficulty	• Simple statically determinate structures built with common construction techniques.

Table 3 Design Supervision Levels

Design Supervision Level (DSL)	Design Supervision Class
DSL3	External independent design check by a chartered design review engineer
DSL2	External independent design check, strongly recommended to be performed by a chartered design review engineer
DSL1	Self-check

- Design Competence Classes (DCC)

These classes should replace the DQL as presented in the current proposal for EN 1990, Annex B. The competence of the designer is relevant for the ability to perform successfully on a project. The described aspects of DQL in the actual proposal of EN 1990´s Annex B like organizational quality are only tools by which a rating of the organisation under consideration is tried. The criteria referred to are not suited for judging the designer´s competence, as this is a purely personal matter. The possible link between CC and DSL can be found in Table 4.

- Design Supervision Levels

Design supervision is the most effective when executed by an independent and external, i.e. not a member of the designing office, engineer fulfilling the responsibilities of the public administration. As soon as substantial damages and fatalities are possible, namely in case of CC2 and CC3, the design review should be solely performed in such a way. For structures which yield only minor failure consequences, a self-check by the design engineer or the corresponding organisation is considered to be sufficient. A possible definition of DSL can be found in Table 3.

The relevant DSL can be determined from the complexity of the task by use of the SC and the severity of the failure consequences in terms of CC as shown in Table 4 and Table 5. Note, that the higher DSL determined from either CC or SC is governing.

- Site Supervision Levels (SSL)

The idea behind SSL is the same as for DSL. Human error must be avoided and this requires inspection (see Table 6).

Table 4 Link of CC and DSL

Consequence Class	Design Supervision Level
CC3	DSL3
CC2	DSL2
CC1	DSL1

Note: The higher DSL determined from Table 4 and Table 5 is governing.

Table 5 Link of SC and DSL

Structural Class	Design Supervision Level
SC3	DSL3
SC2	DSL2
SC1	DSL1

Note: The higher DSL determined from Table 4 and Table 5 is governing.

6.3 Verification

The proposed preventive system has been applied for decades and enjoys wide acceptance among design engineers as well as design review engineers. The presented proposal puts together the best characteristics of already verified and accepted systems and amalgamates them into one optimized approach.

Table 6 Link of SSL and DSL

Site Supervision Level (SSL)	Design Supervision Class
SSL3	External independent check by a licensed design check engineer
SSL2	External independent check, preferably by a licensed design check engineer
SSL1	Self-check

7 Summary and Conclusion

The main cause for structural failures is human error which again is caused by a number of other causes. These need to be covered efficiently by a reliability management system which is systematic and efficient. The current proposal for EN 1990 [9], Annex B, provides a system that allows for adoption in national legislation with relevant modifications. A proposal for a modified system, aiming at the utmost avoidance of human error, has been presented in this paper. The proposal is composed of different widely accepted aspects of available systems and thus represents an optimized approach to avoidance of human error.

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19th IABSE Congress Stockholm, 21-23 September 2016
Challenges in Design and Construction of an Innovative and Sustainable Built Environment

Ein empirisch verifiziertes System für Qualitäts- und Zuverlässigkeitsmanagement

Der vorliegende Beitrag befasst sich mit den Ursachen für Fälle von Tragwerksversagen und den Möglichkeiten, um diese mit Hilfe von Qualitäts- und Zuverlässigkeitsmanagementsystemen zu verhindern. EN 1990 (Anhang B) enthält einen Vorschlag für ein solches System, für den im vorliegenden Beitrag ein Optimierungsvorschlag vorgestellt wird.

In der Bemessung werden in der Regel Teilsicherheitsbeiwerte verwendet, die auf probabilistischen Analysen beruhen. Diese haben den Zweck, die Streuung der Materialparameter, die Auftretenswahrscheinlichkeit bestimmter Lastfälle etc. zu erfassen, um so ein ausreichend hohes Zuverlässigkeitsniveau zu gewährleisten. Menschliche Fehler im Planungs- und Ausführungsprozess lassen sich hierbei jedoch mathematisch nicht einheitlich berücksichtigen. Studien haben gezeigt, dass lediglich in ca. 6 % aller Fälle unvorhersehbare Ereignisse zu einem Tragwerksversagen geführt haben, der restliche Anteil resultierte aus menschlichen Fehlhandlungen.

Menschliche Fehlhandlungen entstehen in vielen Fällen durch kulturelle und systematische Ursachen. Um diesen Fehlerquellen entgegenzuwirken, ist es erforderlich, ein Qualitätsmanagementsystem (QMS) bzw. ein Zuverlässigkeitsmanagementsystem (RMS) einzusetzen, das im besten Fall den gesamten Planungs- wie auch Ausführungsprozess berücksichtigt. Das QMS/RMS regelt die bautechnische Prüfung von Planungsunterlagen und Ausführung.

Einige wesentliche Elemente sind in einem QMS/RMS zu Grunde zu legen. So ist z.B. die Berücksichtigung der Komplexität eines Bauvorhabens in Verbindung mit der Schwere der Versagensfolge wesentlich. Unterschiedliche Niveaus der bautechnischen Prüfung werden definiert. Auch ein kultureller Wandel wird beschrieben, bei dem die Honorarlisten für Ingenieure auch auf private Bauvorhaben übertragen werden, um Preisdumping zu vermeiden.

Das vorgeschlagene QMS/RMS orientiert sich am System, welches im zum Zeitpunkt der Erstellung vorliegenden Entwurf von EN 1990 vorgestellt wurde. Das System wird ergänzt um die zuvor genannten Faktoren. Die bautechnische Prüfung durch einen unabhängigen Prüfingenieur wird als Ideal identifiziert.

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Failure Identification: Procedural Causes and Corresponding Responsibilities

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DOI: 10.2749/101686617X14881937385160

Abstract

When structural members fail, there must be a physical cause, such as missing reinforcement or failing supports. The physical cause itself is often triggered by deficits in the design, in the execution and in the chosen reliability management procedures. Consequently, these deficits determine the level of responsibility for the failure of the involved parties. Human error generally plays a major role in the development of procedural issues; thus, the focus of avoidance in a reliability management system is of special importance. This paper defines the relevant aspects of a reliability management system, introduces practical examples of failure investigations and outlines the related measures to avoid human error that may have contributed to the failure.

Keywords: case study; failure cause; forensic assessment; reliability management system; design supervision.

Introduction

The protection of human life and its physical integrity are fundamental human rights and, consequently, a crucial part of a nation's legal framework. In this paper, the term "structural failure" is used to describe a catastrophic event that may cause severe injuries and loss of human life as well as damages to surrounding structures and the environment. Failure in fulfilling limit states other than the ultimate limit state (e.g. serviceability, durability) is not within the scope of this paper as the reliability management measures applied in most countries do not cover these issues. In case of infrastructure, the impact of structural failure on society and economy is especially significant. Total safety corresponding to a complete absence of structural failures is impossible. To provide the utmost safety without making structures inefficient and unaffordable, different approaches for building control have been chosen by various countries. In design, sufficient structural integrity is thought to be achieved through the application of partial safety factors that are deemed to define the necessary margin between the design value of the actions and the design value of resistances. Safety factors are derived from prediction models and stochastic assessment, that is, the design problem is formulated under uncertainty to account for variations in so-called (random) basic variables such as load magnitude, material strengths, geometrical deviations, uncertainty in the prediction models, etc. From there, the reliability of a structural component can be determined through the use of advanced algorithms (see Refs. [[1, [2] for further information). Reliability is a characteristic property of a member that can be compared to the target reliability that is given in design codes (e.g. in Europe EN 1990)[3]. From the reliability analyses, deterministic approaches to account for the reliability of structural members are derived, with the concept based on partial safety factors being the most widely used. In other words, partial safety factors account for uncertainty related to exceeding actions and material as well as geometric structural properties falling below the reference levels. This explains why the number of structural failures due to extreme actions in combination with significant deficits in structural strengths is fairly low (see Responsibilities). However, probabilistic models describe uncertainty under a set of preset conditions. Reasonable deviations from the nominal values applied in design are thought to be included in this uncertainty. Human errors, however, likely lead to entirely new conditions as these are not covered by the mentioned probabilistic models. Thus, the academic structural system "without errors" requires a totally different verification than the real-world structural system "with errors", that is, the partial safety factors commonly applied in design do not account for human errors. In a conventional forensic engineering assessment, the physical cause for a failure is derived and assessed with an emphasis on the correct application of design codes. It is, however, more crucial to be aware of possible fields of human errors and the required mechanisms and methods to avoid them as structural failure happens mostly due to human errors (see next section). These mechanisms and methods have to be known and understood to provide a comprehensive forensic engineering assessment.

Peer-reviewed by international experts and accepted for publication by SEI Editorial Board

Paper received: August 5, 2016
Paper accepted: December 27, 2016

Failure Causes

Structural failures have been documented since the recording of events. In ancient times, structural failures were considered to be acts of God as the events were often disastrous and unforeseeable. Nowadays, structural analysis allows for scientific verification of the structural integrity. However, structural failures still occur. Researching the structural failures in the past shows that the causes can primarily be categorised by:

A. Failures due to unforeseeably high actions or insufficient structural strength
B. Failures due to human error

Cause A refers to structures with appropriate design according to the valid design standards and codes at the time of construction. Failure then occurred due to extremely high loads that exceed the characteristic value of the actions according to the appropriate codes in conjunction with low material strength. Failure due to this cause is unlikely and normally covered by safety concepts (such as partial safety factors), as mentioned in the Introduction section.

Cause of failure	Total damages
Ignorance, carelessness	37%
Insufficient knowledge	27%
Underestimation of influences	14%
Forgetfulness and mistakes	10%
Unjustified reliance on others	6%
Objectively unknown situations and influences	6%

Table 1: Causes and distribution of structural failures according to Ref. [4] (published in Ref. [10])

Cause B is responsible for failure in almost every case—failure commonly includes some kind of human error. Errors in the development of design guidelines and rules are excluded from the definition of human error here. *Table 1* shows the typical causes for structural failures in a more detailed manner. The table is based on the findings of Ref. [4]. In the corresponding analysis, only 6% of failures were found to be caused by unforeseeable events. The by far larger portion of failures is caused by human error that could have been prevented by proper measures.

Human error can occur at every stage of planning and construction, not only during design. Therefore, it has to be taken into account and avoided during design and execution as well as during service. According to Ref. [5], human error is divided almost evenly between design and construction phases. Additionally, the often referred to “calculation flaw” has proven to be only a minor reason for a serious design error. Failure does not necessarily happen within the first years in the service life of a structure, even though it is more likely. As failure is linked to human error in almost every case, the forensic engineer’s main responsibility is the identification of such errors after a case of failure.

To be able to do this, the forensic engineer needs to be aware that human errors of the types provided in *Table 1* do not happen without a reason. The commonly mentioned reasons according to Ref. [6] are:

- Time pressure, too low engineering fees
- Pressure to minimise the costs of the structure to be built
- Insufficient coordination of the design
- Black-box type of design software
- Lack of detailing
- Large number of new standards and design rules

It becomes clear that human error, and consequently structural failure, is caused to a large extent by systematic and cultural issues (pay grids, time pressure), and thus, the identification of structural failure must also happen systematically.

The two main causes for structural failure, as mentioned above, must be tackled efficiently by the structural codes. While cause A—failure due to unforeseeably high actions or insufficient structural strength—can be counteracted by design concepts in structural codes, cause B—human error—requires an organisational set of measures, referred to as quality or reliability management system (QMS or RMS). Possible QMS or RMS may be provided in design codes, such as EN 1990,[3] Annex B. The presented sets of measures mostly include design supervision and site inspections, which have proven to be effective methods to identify and prevent human errors (see Ref. [7]). While the aforementioned cultural issues need to be assessed by lawyers, the fulfilment of due diligence and the correct application of an RMS need to be assessed by the forensic engineer.

Case Studies

General

The application of an RMS and the corresponding assessments will be explained and detailed by introducing two case studies of real forensic assessments.

Case Study 1: Roof Collapse

Part of the roof of a structure that was used as combined storage and a community centre collapsed after heavy snowfall in Alberta, Canada. The snowfall was not untypical and had been experienced before over the previous 30 years of the building’s service life. The one-storey building’s dimensions were approximately 50 m × 30 m at a height of about 8 m. The outside walls were reinforced concrete blocks. The roof structure consisted of two single-span timber girders resting on the outside walls on one end and a centre glulam beam on the other.

One half of the roof collapsed and deformed the rear walls when it fell. The other half of the roof structure remained in its place and did not appear to have shifted or been damaged (*Fig. 1*). The glulam beam also appeared unharmed. About 4 weeks after the first collapse, the rest of the roof collapsed suddenly—about 10 min after a site inspection. The following investigation proved that the design of the trusses was flawless. However, the installation of the roof trusses was not. Some of the trusses were damaged initially and were also installed incorrectly, resulting in larger buckling length of the top chords. Over time, the damage increased until the massive snow load broke one truss and caused progressive failure to the roof. The collapse of the first part of the roof caused a displacement in the remaining trusses, which then was further followed by progressive failure of the rest of the roof structure.

Thus, the actual failure cause happened at installation. An experienced engineer would likely have noticed the issue at installation. However, the RMS that was valid at the time of construction did not include an independent design and execution inspection. The designing engineer, often an employee of the truss manufacturer, signs off on the design and shop drawings. Another check of the installation is not required. Prevention of the failure would have been possible only if the execution had been checked.

The Alberta building code requires a coordinating professional (architect or engineer) to consolidate documentation from the involved consultants. However, in the end, the owner has to sign and validate that site inspections and substantial compliance with the code is provided. This is equal to a repressive system (see Repressive System section).

However, larger projects require a second seal for the design check on the drawings. Smaller projects normally do not. Residential projects, if engineered at all, only require one seal. The seal can be provided from another registered engineering professional who is not required to be a specialist in structural engineering—any licensed professional engineer, for example, electrical engineers, can sign off. It can be seen that the requirement for design checking is strongly linked to the type of project, and the corresponding failure consequences. Thus, in part, Alberta applies a preventive system depending on the kind of structure. The overall system is a combination of repressive and preventive systems.

After an extensive investigation, the incorrect installation of the trusses leading to a heavily reduced buckling resistance of the top chords was determined as the cause of failure. In the case at hand, neither the design engineer nor the contractor was required to check the execution. Site inspections would have required a special assignment by the owner. Therefore, the responsibility lies with the owner who would have to prove negligence or false work by the involved design engineer or contractor. To evaluate the responsibilities, the forensic engineer needs deep knowledge of the Alberta system, needs to be able to evaluate the kind of structure and needs to be familiar with the corresponding procedure.

Case Study 2: Falsework Collapse

A steel bridge, constructed in the early 1900s, was being replaced by a new reinforced concrete bridge. The collapse happened when the approximately 120 m long reinforced concrete bridge section was being shifted from the location where it was being produced to the final position. The falsework had been used for shifting as well as for the transfer of the loads due to the concreting (*Fig. 2*).

The forensic assessment showed that the failure happened due to a combination of a number of causes. First, the bracing of the framework was not designed to act as a true load-bearing member that would require full structural verification. Second, during the shifting process, the structural system of the falsework changed and became kinematic. These two mentioned causes point out that the planning of the shifting as well as the design of the framework and falsework were contradictory. This had not been discovered by the design review. Another cause was the much early cut-off of the cantilevering framework, which had been connected to a braced section.

The failure occurred due to a sophisticated combination of causes. The causes for the failure in this case were triggered by miscommunication between the parties involved.

Regarding the forensic assessment, an obvious cause that could have triggered the entire failure could not be determined. All mentioned causes contributed. This makes the forensic assessment more complex in terms of evaluating possible responsibilities. The fact that the application of an RMS does not only make design errors less likely but also makes the forensic assessment more difficult and time-consuming, which should be considered right from the start in a forensic assessment. If a working RMS was applied, which should be the first aspect to be checked, the forensic assessment will likely not deliver simple answers.

Responsibilities

General

The RMS is often part of a legal framework. Thus, the actual responsibilities will and have to be determined in a court of law. However, the responsibilities in the application of an RMS can be assessed from the technical point of view as it consists of procedures and methods that should be applied correctly. The duty of the forensic engineer in assessing a case of failure is thus to also check whether these methods and procedures have been applied correctly. From practical experience, the authors would like to mention that in many cases, forensic engineers limit their assessment to the mechanical aspects of a failure. As an example, the overload of a beam may be the physical cause for failure, although the actual reason may be the negligence of a site inspection as stipulated in the RMS. The forensic assessment will then often produce a report that states the overload as a reason, and consequently, it will be up to counsel to determine whether an RMS was applied correctly or not. If the assessment of the RMS became part of the forensic engineer's assessment, the complete investigations could be more efficient. A reason for this is that forensic engineers understand RMS as another technical aspect of achieving reliable structures.

RMSs are different internationally. The respective state administrates this responsibility by granting building permits. The RMS is consequently linked to the building permit. Every state has different legislation so that the RMSs exhibit minor or major differences. However, the RMS can be divided into two general types depending on the main approach to the avoidance of structural failures.

Fig. 1: Remaining roof structure from case study 1

Fig. 2: Debris of formwork from case study 2

Repressive System

A typical version of a repressive system is explained by an example system applied in France. For the issuing of a building permit, the building authorities only check zoning aspects and the building masterplan. Structural integrity is within the responsibility of the parties involved with the construction: architect, contractor and owner who are legally obligated to build up to the relevant codes. However, fulfilment is not to be checked by the authorities. The parties are also legally obligated to take out insurance policies to cover risks associated with the construction.

The advantage of this system is the financial safety in case of failure and damages as the insurance will cover possible claims. However, disadvantages are substantial—reliability management does not happen to prevent failure in the first place, and the structural cost increases significantly due to the cost of the insurance policies. Design reviewing and site inspections are only performed if an involved party specifically requires these, for example, the insurance company might grant better policy conditions for the owner if design reviewing is performed. Compared with the above identified causes for structural failure, the following must be stated.

Cause A (unforeseeably high actions or insufficient structural strength) and Cause B (human error) are not necessarily covered as there is no legal requirement to review the design before the building permit is granted. A building permit can be obtained without design and execution supervision. However, design and execution supervision often happens under private law.

Preventive System

Contrary to the repressive system, the preventive system tries to avoid structural failure in general by consequent design supervision, before the permit is granted, and on-site inspections for checking the execution. A typical example for a preventive system is the one applied in Germany, presented in *Fig. 3*. In this system, a full design review has to be performed by a highly qualified and chartered design review engineer and reported to the building authorities before the building permit is granted. During construction, the design review engineer is responsible for checking all the relevant design drawings as well as for performing sample inspections of the execution (e.g. reinforcement *in situ*). The disadvantages of this system lie within the possibly larger inertia in the design and execution phase as an additional, economically independent party is involved. However, this additional player introduces advantages into the design and execution process as he provides the prevention of failures and cost-efficiency as additional insurance policies are not required. Compared with the identified causes for structural failure, the following must be stated.

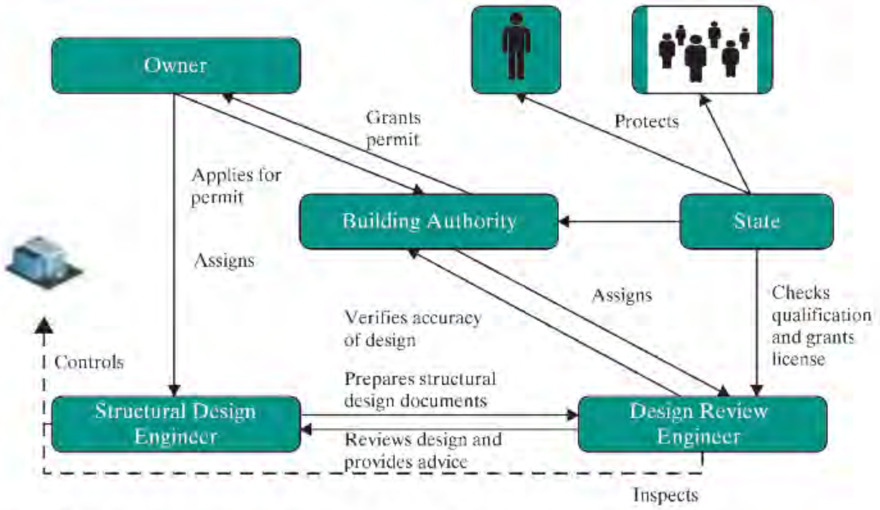

Fig. 3: Preventive system using the example of the German system

The first and second causes are covered as there is a legal requirement to check the design before the building permit is granted, for example, in Germany, the detailed report of the design check is a requirement for granting a permit. A building permit cannot be obtained without design and execution supervision. After completion, the design review engineer has to provide another report.

The preventive system is sometimes criticised for the possible relying of the design engineer on the design review engineer, leading to a flawed design in the hope that the design review engineer will find mistakes. From the author's experience as a consulting engineer, however, this is generally not the case because the design engineer understands the liability issue (the liability lies with the design engineer, not the design review engineer), and a flawed design will harm the firm's reputation. Additionally, the design review engineer does not solve possible mistakes for the design engineer; he will require additional documentation and verification. This again leads to more effort. Thus, relying on "design aid" by the design review engineer will only cause an inefficient design and disadvantages for the design engineer.

Influence on Forensic Engineer's Assessment

From the above explanations, it becomes obvious that in a repressive system and a preventive system, assessments of the forensic engineer have to be different. As the building permit already proves that a design check has been conducted in a preventive system, the likelihood that an error in design led to the failure at hand is lower than in the case of the situation in a repressive system. Here, whether a design check was required and conducted has to be verified first. Thus, the forensic engineer's assessment starts at a different level. It can be stated that:

1. In a preventive RMS, the forensic assessment should start with an assessment of the execution works. Only if a comprehensive cause cannot be determined should the design be revisited. If a cause in the execution was determined, however, a limited check of the conformity of execution and design for the respective member should be conducted.
2. In a repressive system, the assessment should start with the design and then be extended to the execution. Alternatively, design and execution should be checked in parallel.

In a preventive system, post-failure assessments may thus be more efficient as it is easier to rule out some failure causes in design. By having greater confidence in the design due to the performed design check, assessments of failure cases after a long period of time post completion are also more efficient as design reviews are very difficult to perform in these cases due to missing design documentation and drawings.

Aspects of an RMS

General

From the previous case studies and findings from the Responsibilities section, the following sections will attempt to create a comprehensive, optimised proposal for an RMS. In this section, the aspects that should be covered in every RMS are derived and explained. All these aspects should also be considered when assessing the application of an RMS.

Efficiency

The effort for reliability management must be adjusted to the task. As an example, it is clear that a nuclear power plant requires more detailed supervision than a town house. Therefore, a general requirement for an RMS is efficiency by means of adjustable requirements. In the forensic engineer's assessment, it must be evaluated whether the applied RMS was sufficient and adequate for the task at hand.

Failure Consequences and Complexity of the Task

To achieve efficient progress in design, the required level of design checking and review must be related to the severity of the failure consequences and the complexity of a structure; that is, structures with a severe impact on society in the case of a structural failure (infrastructure, large number of possible fatalities, etc.) as well as highly complex structures (shells etc.) require higher levels of checking and review than simple structures or structures that will not cause severe failure consequences.

Relevant Levels of Design Checking and Review and Site Inspections

Design checking and review and site inspections are very important as they tackle both the previously identified causes for structural failures (see Failure Causes). By assuring that the design and execution have been performed according to the relevant design codes, the probability of failure due to unforeseeably high actions or insufficient structural strength can be minimised. However, the main task in design review and checking is the discovery of human error. In an RMS, the required level of design supervision and site inspections must be detailed. In general, both can happen at different levels:

1. Self-check

Plausibility checks of design are performed by the (design) engineer himself or herself as every engineer does every day, for example, by using a pencil and an eraser.

2. Internal review

The design is reviewed by another person within the same design organisation. The possible spectrum of this method can range from discussion with a colleague to a check procedure run by a specialised department. The effectiveness increases with the chosen procedures and the independence—technically as well as economically—of the reviewing body.

3. External review

The design and execution is reviewed by an specially assigned organisation that is completely independent from the design organisation. This is a very effective method due to the lack of shared interest between the design and review organisation.

4. External review by an independent, chartered expert

The effectiveness of the review increases with the qualification of the reviewer. In some states, reviewers who had to undergo elaborate licensing examinations (chartering) perform the design review by fulfilling the responsibilities of the public administration. These individuals provide different angles, insight and extensive experience and often not only support efficiently in eliminating errors but also help improve the original design. This is considered to be the highest level of design review.

Possible criticism to licensing and chartering is the fact that the sole volume of required design checking exceeds the capacities of single (licensed) design review engineers. Because of this, the design review engineers will normally require a team of engineers working for him or her. However, the superior qualification of the design engineer is necessary to point out weaknesses in the design and pose the "right" questions when provided with the results of the design review. It should be within the responsibility of the design review engineer to choose the project team wisely and with the highest level of trust. The composition of the team and the required leadership abilities are another reason why the licensed design review engineer must be exceptionally qualified. Pure design proficiency is not enough.

In addition to the design review, site inspections are required to verify the correct transfer from the abstract design level to the actually built state. The inspections can be performed by different parties and at different stages comparable to the aforementioned ones.

Self-check and internal review will hardly be documented or available to the forensic engineer. If an external check had not been performed or assigned, it is almost impossible to prove the required design supervision, which will shift the responsibility towards the client.

Qualification of Designer and Design Review Engineer

Owing to the varying complexities of structures, the required qualification of the design engineer plays a major role in providing high-quality design. Qualification of the design engineer is often understood as the background in the form of academic degrees and relevant experience. Additionally, the capacity of the organisational background in which the engineer acts may have an impact on the capability of the engineer. For example, an excellent engineer working alone on a large-scale project may be overwhelmed, while an inadequate engineer will not necessarily succeed because of the support of a large engineering firm. There are many examples of small engineering firms that excel in large-scale projects due to the organisational efficiency, while large companies may be slow in processing due to the organisational overhead and vice versa. The link of engineering qualification solely to the organisational size, processes and capacity is not purposeful and will not provide sufficient answers. Furthermore, qualification must be based and assessed on a three-dimensional level: personal, technical and organisational qualification. This is especially important when it comes to the qualification of the design review engineer. The design review must not only be understood as a search for errors and flaws—it also opens up the chance of an independent second opinion with a possibility of improvement and optimisation of the design at hand.

When assessing the correct application of an RMS, the design qualification must also be assessed. Often, the design qualification has to be proven before assignment by providing references. However, this is not impartial as references can be modified and are hard to check. The forensic engineer should communicate closely with counsel to determine whether an engineering firm was actually qualified to provide the assigned services. This is not only related to engineering competence but also to the available resources.

A Proposal for an Optimised RMS Allowing for Improved Forensic Assessment

General

Failure must be prevented. Total failure prevention is impossible due to human error. A working RMS is required to minimise the cases of failure. It is the forensic engineer's responsibility to provide the lessons learned from structural failures and introduce them into the technical discussion to improve the built environment for future generations. Thus, a proposal for an optimised RMS will be provided in this section.

Different approaches exist depending on national legislation and culture. The aspects mentioned in Aspects of an RMS section define an RMS and must be addressed in the forensic engineer's assessment. The design qualification criteria and the requirements in terms of design and site supervision especially need to be addressed in an RMS and require thorough assessment by the forensic engineer.

Preventive System

As mentioned in Repressive System section, a preventive system covers the identified causes for structural failure efficiently and should be preferred. This generally means that the building permit should be linked to design and execution supervision.

Proposed Classes

From the elaborations above, the following classes should be introduced and applied consequently within an efficient RMS to cover the identified required elements from Aspects of an RMS section.

- Consequence classes (CC)

The consequences of failure must be used to determine the required effort for design and site supervision. Consequence classes are defined in, for example, EN 1990[3] and presented in *Table 2*.

- Structural classes (SC)

Complexity as a measure for errorproneness must be combined with the relevant consequence class. In Germany, structures are grouped into different structural classes in state law (see [8]; also see *Table 3*). Also, the engineering fee from the national pay grid (see [9]) depends on the complexity of the structure.

- Design competence classes

The possible link between CC and design supervision level (DSL; *Table 4*) can be found in *Table 5*.

- Design supervision levels

Design supervision is an effective tool to tackle human error. It can be assumed that it may be especially effective when executed by an

Consequence class	Failure consequences	Example of buildings and civil engineering works
CC3	**High** consequence for loss of human life *or* economic, social or environmental consequences **very great**	Grandstands, public buildings where consequences of failure are high (e.g. a concert hall)
CC2	**Medium** consequence for loss of human life; economic, social or environmental consequences **considerable**	Residential and office buildings, public buildings where consequences of failure are medium (e.g. an office building)
CC1	**Low** consequence for loss of human life, *and* economic, social or environmental consequences **small or negligible**	Agricultural buildings where people do not normally enter (e.g. storage buildings, greenhouses)

Table 2: Consequence classes

Structural classes	Level of difficulty	Characteristics and examples
SC 3	Structures with a high level of difficulty	• Complex statically indeterminate structures • Structures with non-trivial load scenarios and action effects • Highly complex structural systems requiring, for example, non-linear calculations or dynamic effects to be considered • Complex structures requiring new design techniques or design assisted by testing • Pre-stressed and post-tensioned structures • Difficult stability considerations required
SC 2	Structures with medium level of difficulty	Difficult statically determinate or statically indeterminate regular structures built with common construction techniques
SC 1	Structures with a low level of difficulty	Simple statically determinate structures built with common construction techniques

Table 3: Structural classes

Design supervision level	Design supervision class
DSL3	External independent design check by a chartered design review engineer
DSL2	External independent design check, strongly recommended to be performed by a chartered design review engineer
DSL1	Self-check

Table 4: Design supervision levels

Consequence class	Design supervision level
CC3	DSL3
CC2	DSL2
CC1	DSL1

The higher DSL determined from *Tables 5* and *6* is governing.

Table 5: Link of consequence class and design supervision level

Structural class	Design supervision level
SC3	DSL3
SC2	DSL2
SC1	DSL1

The higher DSL determined from *Tables 5* and *6* is governing.

Table 6: Link of structural class and design supervision level

independent, external (i.e. not a member of the designing office to guarantee objectivity) engineer fulfilling the responsibilities of the public administration. In case of CC2 and CC3 (see *Table 2*), namely, when substantial damages and fatalities are possible, it is recommended that the design review be performed in such a way. For structures that yield only minor failure consequences, a self-check by the design engineer or the corresponding organisation is sufficient. A possible definition of DSL can be found in *Table 4*.

The relevant DSL can be determined from the complexity of the task through the use of the SC and the severity of the failure consequences in terms of CC as shown in *Tables 5* and *6*. Note that the higher DSL determined from either CC or SC is governing.

- Site supervision levels (SSL)

The idea behind SSL is the same as for DSL. Human error must be avoided, and this requires inspection.

Conclusions

Sophisticated skills in mechanics and physics will not necessarily provide the required answers in terms of the determination of responsibilities after a structural failure. However, these skills form the basis for any assessment. Once the physical cause has been identified, responsibilities can be determined. Note that the term "responsibility" refers to the responsibility of a person to perform in a certain way from a technical point of view. It does not refer to responsibilities in the form of liability—the determination of these is the purpose of a court of law, that is, a judge. The case studies showed that a deep understanding of reliability management is essential for the determination of responsibilities—and this requires the forensic engineer to be fully aware of the legal environment and the relevant RMS, especially in an international setting. However, it becomes clear that the forensic engineer should start his assessment, once all data are collected, with the assessment of the RMS and application issues. From there, the level of detailing can be estimated, and the focus of the assessment can be set.

To prevent failures and avoid the loss of human life associated with structural failures, the necessary aspects of an RMS are evaluated and provided along with a proposal for an optimised RMS.

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Fehleridentifizierung: Ursachen im Bauprozess und entsprechende Verantwortlichkeiten

Der Schutz des menschlichen Lebens und körperliche Unversehrtheit sind grundlegende Menschenrechte und folglich ein fundamentaler Bestandteil der Gesetzgebung einer Nation. Der vorliegende Artikel befasst sich daher mit der Vorgehensweise bei der Fehlerfindung in Fällen von Tragwerksversagen und der hiermit einhergehenden Verantwortlichkeitsfrage.

Jede Bemessung auf Basis des Eurocode legt Teilsicherheitsbeiwerte zu Grunde, die auf probabilistischen Analysen beruhen. Diese haben den Zweck, die Streuung der Materialparameter, die Auftretenswahrscheinlichkeit bestimmter Lastfälle etc. zu erfassen und so ein ausreichendes Zuverlässigkeitsniveau zu gewährleisten. Menschliche Fehler im Planungs- und Ausführungsprozess lassen sich hierbei mathematisch jedoch nicht einheitlich berücksichtigen. Studien haben gezeigt, dass lediglich in ca. 6 % aller Fälle unvorhersehbare Ereignisse zu einem Tragwerksversagen geführt haben, der restliche Anteil resultierte aus menschlichen Fehlern. Um dieser Fehlerquelle entgegenzuwirken, ist es erforderlich, ein Qualitätsmanagementsystem (QMS) bzw. ein Zuverlässigkeitsmanagementsystem (RMS) einzusetzen, das im besten Fall den gesamten Planungs- wie auch Ausführungsprozess betrachtet.

Im Versagensfall bedarf es eines sachverständigen Ingenieurs, dessen Aufgabe es ist, die Erfüllung der Sorgfaltspflicht aller Beteiligten und die korrekte Anwendung eines RMS zu prüfen. Anhand von zwei Analysen realer Fallstudien wird dies verdeutlicht und gezeigt, wie wichtig es ist, die nationalen Regelungen eines RMS exakt zu kennen. Es reicht hierbei nicht aus, die Fehlerursache auf mechanische Gründe zu beschränken, oftmals resultiert diese erst aus einer Kettenreaktion von vorherigen Fehlern, wie z.B. mangelhaften Kontrollen.

Ein sachverständiger Ingenieur sollte zunächst bedenken, welche Form des RMS vorliegt. Bei einem repressiven System, wie z.B. in Frankreich, verhindert das RMS den Ausfall des Systems gar nicht erst, da die Schäden hier von Versicherungen getragen werden. In diesem Fall sollte das Gutachten mit der Bemessung beginnen und auf die Ausführung ausgedehnt werden. Wenn jedoch ein präventives System, wie z.B. in Deutschland, vorliegt, so ist eine konsequente Planungsüberwachung vorgeschrieben, wodurch in der Untersuchung zunächst vor allem die Ausführung analysiert werden sollte.

Abschließend wird empfohlen, ein optimiertes RMS auf der Basis des präventiven Systems zu entwickeln. In anderen Worten: die Baugenehmigung sollte mit der Planungs- und Ausführungsüberwachung verknüpft sein, um das Fehlerpotential in einem Projekt zu minimieren. Die Komplexität und mögliche Schadensfolgen in einem Projekt sind hierbei stets zu beachten. So wird die Kategorisierung jedes Projekts in Schadensfolgeklassen, Gebäudeklassen, Überwachungsklassen, bautechnische Prüfungsklassen und ausführungstechnische Prüfungsklassen vorgeschlagen. Entsprechend dieser Kategorisierung ist die Eignung eines zuständigen Tragwerkplaners und Prüfingenieurs anhand der persönlichen, der technischen und auch der organisatorischen Qualifikation zu prüfen. Hierbei sollte der Fokus nicht auf den akademischen Abschluss des Planers, die Größe des Büros und die angegebenen Referenzen begrenzt werden.

39th IABSE Symposium – *Engineering the Future*
September 21-23 2017, Vancouver, Canada

Influences on Determining Structural Reliability

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Abstract

The influences to investigate when trying to assess the reliability of structures are manifold. Even if all the relevant stochastic parameters and data for establishing a typical reliability model are known, there are uncertainties to be considered which cannot be covered by probabilistic methods only. In a probabilistic analysis, the basic variables of a design problem, such as e.g. material strength or load effects, have to be modelled as random variables. From there, the failure probability of a member can be determined by use of methods of reliability analysis.

This relatively straightforward procedure reaches its limits when additional influences like the simplification and/or linearization of the design problem, the model-reality-antagonism, the paper-building site transformation or human error are to be considered. Especially the three latter are not tangible by stochastic methods only. As the nature of these issues is predominantly human, individual competence or its opposite deprive a purely mathematical approach to achieving sufficient reliability.

Keywords: reliability, design checking, design supervision, human error, model uncertainty

1 Introduction

The protection of human life and its physical integrity are fundamental human rights. Structural failure is a catastrophic event that may cause severe injuries and loss of human life as well as damages to surrounding structures and the environment. In case of infrastructure, the impact of structural failure on society and economy is especially significant. Thus, structural failure must be effectively prevented by suited means.

In this context, reliability is often referred to as a measure for a structural member's safety. This is fundamentally false – reliability represents an operative property of a member. It can be calculated for every member and is, thus, closer to being a property such as material strength than an actual measure for structural safety.

The actual problem when it comes to the discussion of structural reliability is the fact that the results often appear to be arbitrary. In reliability analysis, many basic parameters need to be estimated due to a lack of data. The stochastic models that can be found in the literature are also not appropriate for every case. On top of this, the inaccuracy of the prediction models (for loads and capacities) needs to be estimated. Keeping in mind that the degree of detailing is limited, it becomes clear that the obtained value of reliability must be interpreted only in the chosen context. Considering that human error is commonly not covered by reliability analysis, it is clear that reliability cannot be seen as a measure of structural safety.

By presentation of case studies of elementary structural problems, this paper will exemplify the impact of human misjudgements on the results of traditional reliability analyses. Identification methods for relevant problems targeting a more coherent structural reliability concept, covering not only the pure stochastic background, will discussed. Based on the conclusions drawn, a suggestion for safe guarding the structural reliability will be made.

2 Causes of Structural Failures

Structural failures have been documented since the recording of events. In ancient times, structural failures were considered to be acts of god since the events were often disastrous and unforeseeable. Nowadays, structural analysis allows for scientific verification of the structural integrity. However, structural failures still occur. Researching the structural failures in the past shows that the causes can primarily be categorized by:

A Failures due to unforeseeably high actions or insufficient structural strength
B Failures due to human error

Cause A refers to structures with appropriate design according to the valid design standards and codes at the time of construction. Failure then occurred due to extremely high loads, that exceed the characteristic value of the actions according to the appropriate codes in conjunction with low material strength. Failure due to this cause is unlikely and normally covered by safety concepts (such as partial safety factors).

Cause B is responsible for failure in almost every case – failure does commonly include human error. Errors in the development of design guidelines and rules are excluded from the definition of human error here. Table 1 shows the typical cuses for structural failures in a more detailed way. The table is based on the findings of [4]. In the corresponding analysis, only 6% of failures were found to be caused by unforeseeable events. The by far larger portion of failures are caused by human error that could have been prevented by proper measures.

Table 1 Causes and distribution of structural failures according to ***[4]*** *(published in* ***[5]****)*

Cause of Failure	% of total damages
Ignorance, Carelessness	37%
Insufficient Knowledge	27%
Underestimation of Influences	14%
Forgetfulness and Mistakes	10%
Unjustified Relying on Others	6%
Objectively Unknown Situations and Influences	6%

Human error can occur at every stage of the development, the realisation and the use of civil engineering structures, not only during design. Therefore, it must be taken into account and avoided during design and execution as well as during service. According to [1], human error is divided almost evenly between design and construction phases. Additionally, the often referred to "calculation flaw" has proven to be only a minor reason for a serious design error.

Human errors of the types provided in Table 1 do not happen without a reason. The commonly mentioned reasons according to [6] are:

- Time pressure, too low engineering fees
- Pressure to minimize the costs of the structure to be built
- Insufficient coordination of the design
- Black-box-type use of design software
- Lack of detailing
- Large number of new standards and design rules

It becomes pretty obvious that human error, and consequently structural failure, is caused to a large extend by systematic and cultural issues (pay grids, time pressure) and thus the prevention of structural failure must tackle the problem systematically, too. The two main causes for structural failure, as mentioned above, must be addressed efficiently. While the cause A – failure due to unforeseeably high actions or insufficient structural strength – can be counteracted by design concepts in structural codes, cause B – human error – requires an organisational set of measures, referred to as **Q**uality or **R**eliability **M**anagement **S**ystem (QMS or RMS). Possible QMS or RMS systems may be provided in design codes, such as EN 1990, Annex B. The presented set of measures mostly includes design supervision and site inspections, which have proven to be the only effective methods to identify and prevent human errors.

3 Verification of Structural Integrity

3.1 General Procedure

In design, sufficient structural integrity is thought to be achieved through application of partial safety factors which are deemed to define the necessary margin of the design values of the actions and the design value of the resistances. Safety factors are derived from prediction models and stochastic assessment, i.e. the design problem is formulated under uncertainty to account for variations in so-called (random) basic variables such as load magnitude, material strengths, geometrical deviations, uncertainty in the prediction models etc. From there, the reliability of a structural component can be determined by use of advanced algorithms (see [2] and [3] for details). Note, that reliability is a characteristic property of a member that can be compared to the target reliability which is given in design codes (e.g. in Europe EN 1990, see *Table 2*).

Table 2 Target reliability according to EN 1990

Limit state	**Target reliability**	
	1 yr	**50 yrs**[a]
Ultimate	4.7	3.8
Fatigue	-	1.5 – 3.8[b]
Serviceability	3.0	

[a] observation period

[b] depending on accessibility, tolerance and maintainability

From the reliability analyses, deterministic approaches to account for the reliability of structural members are derived, with the concept based on partial safety factors being the most widely used one. In other words, partial safety factors account for uncertainty related to exceeding actions and material as well as geometric structural properties falling below the reference levels. This explains why the number of structural failures due to extreme actions in combination with significant deficits in structural strengths is fairly low (see [1] and [4]). However, probabilistic models describe uncertainty under a set of pre-set conditions. Reasonable deviations from the nominal values applied in design are thought to be included in this uncertainty. Human errors, however, likely lead to entirely new conditions as these are not covered by the mentioned probabilistic models. Thus, the academic structural system "without errors" requires a totally different verification than the real-world structural system "with errors", i.e. the partial safety factors commonly applied in design do not account for human errors.

3.2 Model Uncertainties

As described before, reliability analyses are often used to determine partial safety factors. Another method that has been applied regularly in the past was calibration of the safety factors based on previous code generations. The latter accounts for a level of reliability that, though not scientifically defined, is considered sufficient. Reliability analysis is different from this because a theoretical level of reliability will be derived based on assumptions made in the analysis for every basic variable. This means, if assumptions are made poorly or the problem cannot be defined clearly, the obtained value of reliability will be inaccurate. Making adequate assumptions is possible for basic variables which can be measured easily (e.g. compressive strength of concrete) and for which sufficient data is available. Other basic variables are much harder to estimate, especially the so-called model uncertainties. These basic variables refer to the uncertainty of the applied prediction models for loads and resistances. A prediction model will always give results that are different from reality due to simplification and lack of knowledge. Models cannot incorporate every parameter, e.g. is the distribution of grain size not a part of common prediction models for the compressive strength of concrete. Also, models can only represent the current state of knowledge which is often not sufficient, e.g. is the load-bearing behaviour of masonry under in-plane shear still not completely known and the prediction models vary significantly in their deviation (see [3]) or the distribution of stress in complex systems is not straightforward.

Therefore, model uncertainties must be estimated based on the problem, the material and further aspects. Among others, the JCSS (see [7]) provides first estimates for model uncertainties. These, however require updating to be improved for the problem at hand. However, updating requires data which is commonly is derived using the "test-to-prediction"-ratio, i.e. a measured value divided by its prediction as a measure for accuracy. This kind of data is hard to obtain for many complex problems.

Because of the mentioned aspects, the model uncertainties are often estimated conservatively and thus, the obtained values of reliability are not accurate.

Additionally, it must be clear that model uncertainties are mostly based on a test-to-prediction ratio that was derived under lab conditions. This cannot be used as a representation of realistic conditions. Especially human error, in design and execution, is significantly likelier in a realistic setting than in a lab. The corresponding differences in reliability are significant and cannot be covered in a reliability analysis by increasing the model uncertainties.

4 Relationship of Human Error and Structural Reliability

4.1 General

From the previous clauses, it should be clear that safety factors are not useful when it comes to covering human errors. However, the authors are regularly confronted with this thought. To provide an idea of the capabilities of partial safety factors in covering human error two examples will be assessed in clauses 4.2 and 4.3. In these fictional examples, a human error occurred. To assess the range of coverage of the partial safety factor concept, the reliability of the using the partial safety factors as required by the Eurocode and assuming an appropriate structural model will be determined and compared to the reliability that was actually provided under consideration of the human error.

The examples are chosen in terms of simplicity and probability of occurrence.

4.2 First Example: Concrete Slab

The first example refers to an error in the execution. Consider a single-span reinforced concrete slab designed according to Eurocode 2. The structurally required reinforcement is a grid on the bottom side, while the grid on the top is required purely due to crack control and ductility. Now, an error in the execution occurs: the top and bottom reinforcement get confused in the drawings so that the structurally required reinforcement ends up on the wrong side of the slab.

To determine the reliability of the slab, a limit state function is required. In this case, flexural failure of the slab will be investigated as the governing failure mode. A general and widely used formulation of the limit state function *j(x)* is presented in eq. 1.

$$j(x) = R - E \qquad (1)$$

From this general form, the limit state function for this case can be derived, see eq. 2, considering a stress-block in accordance with EN 1992-1-1, 3.1.7. Note, that the limit state is reached when *j(x)* equals 0.

$$\theta_R \cdot A_s \cdot f_y - \theta_E \cdot \frac{(g + q_1 + q_2) \cdot l^2}{\frac{32}{5} \cdot d} = 0 \qquad (2)$$

The characteristic (code) values of the loads applied in the code design are $g_k = 5.0$ kN/m², $g_{k2} = 1.0$ kN/m² and $q_k = 2.5$ kN/m² (live load in a residential building). The structurally required reinforcement A_s is 5.24 cm²/m and the reinforcement in the opposite layer is chosen to be 1.88 cm²/m.

The corresponding stochastic model was chosen based on [7] and is provided in Table 3. Note, that the characteristic values do not represent the mean of the basic variables in most cases. While the characteristic value e.g. for dead load is defined as the mean, the characteristic value for live load is normally defined as 98%-quantile. For the stochastic model, the means had to be derived assuming a type of distribution and corresponding scatter.

With these assumptions, the provided value of reliability *without the mentioned error* can be calculated to $\beta = 3.8$ using Second Order Reliability Method (SORM). *With the error,* β becomes negative, which means that the probability of failure $P_f \geq 1$ (certain failure). Thus, a verification is impossible. The partial safety factor on the steel strength would have required a value of $\gamma_M \geq 2.9$ to achieve the code target reliability – this equals almost tripling the characteristic value of the yield strength. This is unrealistic and inefficient. Consequently, structural integrity could only be provided by effective design review.

4.3 Second Example: Steel Column

In this theoretical example, consider a steel column. In the original design, it was assumed that the floor at the top of the columns acts as horizontal support. However, an error is determined: due to several expansion joints in the floor structure, a horizontal support is not provided by the floor structure. Consequently, the buckling length of the column changes significantly.

The theoretical level of reliability will be provided for both cases, with and without error.

To check the reliability a simplified approach is chosen, taking into account the ideal Euler buckling load for the formulation of the limit state function similar to eq. 1. Using this, the required moment of inertia I is determined that corresponds to a full utilization of the cross-section for the case without human error. The same I will then be inserted to determine the reliability for the case with error. The error leads to a difference between the two cases in buckling length which doubles from a single-span column to a cantilevering one. Eq. 3 gives the applied limit state function and Table 3 provides the applied stochastic model.

Table 3. Stochastic model for examples 1 & 2

Quantity	Dist.	Mean	CoV
f_y	LN	560 N/mm²	5.3%
A_s	N	5.24 cm²/m[a] 1.88 cm²/m[b]	2%[a] 5.5%[b]
g	N	5.0 kN/m²	4%
q_1	N	1.0 kN/m²	4%
q_2	GUM	0.15 kN/m²	90%
l	const.	-	-
d	const.	-	-
Θ_L	LN	1.0[c] 1.0[d]	10%[c] 5%[d]
Θ_R	LN	1.2[c] 1.4[d]	15%[c] 25%[d]
E	N	210,000 N/mm²	3%
N_G	N	300 kN	2%
N_Q	GUM	150 kN	90%
s_k	N	4.0 m[a] 8.0 m[b]	0.5%[a] 0.25%[b]
I	N	892 cm⁴	2%

[a]without error
[b]with error
[c]example 1
[d]example 2

$$\theta_R \cdot \left(\frac{\pi}{s_k}\right)^2 \cdot E \cdot I - \theta_E \cdot \left(N_G + N_Q\right) = 0 \qquad (3)$$

The obtained values of reliability are $\beta = 3.3$ for the unflawed case and $\beta<0$ for the case under error. This again shows how a possible, realistic error in the structural model cannot be covered by conservative partial safety factors.

4.4 Conclusion

The examples provided in clauses 4.2 and 4.3 showed two typical scenarios of human errors as they occur in day-to-day practice. The values of reliability derived from the examples, with and without the error, clearly show that human error alters the limit state function and the value of reliability drastically to an extent that could only be covered by very high and inefficient partial safety factors. Even larger consequences can be expected when the human error also alters the occurring failure mode, e.g. from assumed flexural failure in the design to punching in reinforced concrete slabs. This will be part of a future study.

It becomes clear that reliability cannot be provided without the avoidance of human error, making design review an integral part of reliability management and control.

5 Authentic Examples of Human Error

5.1 General

In the previous clause, two theoretical examples of human error were provided and the consequence in terms of reliability were shown. In this clause, examples of actually occurred human errors will be presented. These examples are authentic.

5.2 Reinforced Concrete Slab

In a larger commercial structure, the design for the base slab had been performed. It included the check against punching. The design was performed correctly, the punching reinforcement as well as the flexural reinforcement was determined correctly according to Eurocode 2. When the execution started and reinforcement drawings were provided, it was found that the additional flexural reinforcement, which was increased to minimize punching reinforcement, was false – it was drawn on the wrong side of the slab. An easy error that could have led to catastrophic consequences. Figure 1 shows the position of the column in the building and Figure 2 shows the reinforcement detail taken from the actual reinforcement drawing.

Figure 1. Position of RC column

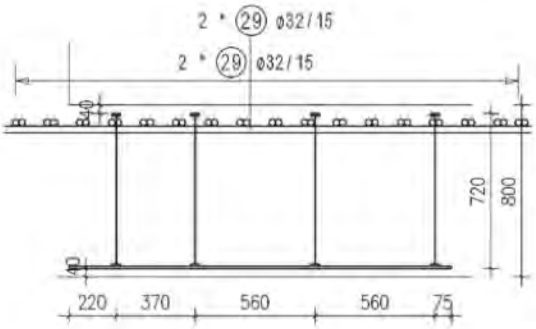

Figure 2. Reinforcement detail

5.3 Buckling Failure of Web-Panels

The main load carrying member in a falsework required for the demolition of a wide-span bridge was a box-girder. The design had been conducted in detail for every load-carrying part, including the stiffened-web-panels at the intermediate supports. The situation at these locations is characterized by biaxial compression in the web-panels due to the negative bending moment and the introduction of the bearing force. The modular character of the falswork girder makes it inevitable that the bearing force will be applied in a significant distance to the vertical stringers directly onto the web-panel. Hence the interaction of biaxial compression when verifying the biuckling resistance of these elements has to be analysed. A 3D FE model of the girder at the support showing the web-panels and the offset of the vertical stringer is presented in Figure 3.

Figure 3. 3D FE-model of the main girder at the intermediate support

The design office had come to the conclusion that the design meets all the requirements of the set of technical rules and regulations. This was true at every point of the structure except for the stifffened-web-panels at the intermediate supports. The design verification procedures were conducted by modelling the stiffened web as a rod subjected to compression. In this model the influence of the lateral compression on the stability of the longitudinal stiffeners was not considered. However, it was found that the influence of the lateral compression was governing in this case and that the design check against plate buckling was not successful. Figure 4 gives an impression of the distribution of the axial (left) and lateral compression (right).

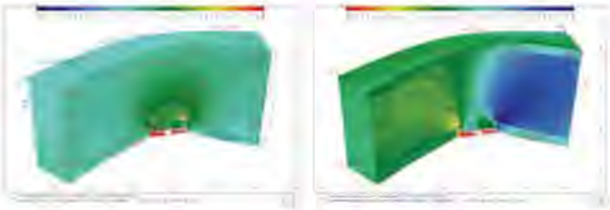

Figure 4. Comparison of axial (left) and lateral compression

5.4 Discrepancies in Modelling Global and Partial Systems

A large complex building of an industrial production plant, consisting of two different, but linked structures was designed by two independent structural design firms, with each covering one of the structures. The link between the structures was assumend, having the completed structural system in mind, as a stiff bracing wall in both partial designs.

The error occurred by neglection of the construction stages. The structures were built subsequently, one after the other. This means, that the stiff bracing wall, was not available to the first structure to be built. This led to severly different deformations and significantly larger forces in the bracing system, and could possibly have been causing structural failure.

Figure 5. Analysis of the partial system with deformations

In Figure 5, the analysis of one partial system is presented with the corresponding deformations due to wind loads. Note the relevant deformations marked by the red square. Also, the resulting tensile force in the vertical bracing system at foundation level was 1,200 kN.

Figure 6 shows the corresponding analysis to the one presented in Figure 5 but for the the coupled systems. Compare the derived deformations. The tensile force in the vertical bracing system at foundation level for this case was 650 kN, roughly half of the tensile force in the construction stage. Hence, one could argue, that the chosen modelling strategy of cutting the two structurcal systems apart, was a conservative one. But by judging the differences in the deformation patterns in Figure 5 and Figure 6, it becomes obvious that the reduction of the forces at foundation level causes remarkable increases of the forces in the horizontal stiffening systems of structure two. When looking into the calculation results, the increase at the critical elements sums up to 500%.

This descreptancy was discovered in the design review – a clear proof for the important role of the design review, not only as "number cruncher" but also as pivotal node of the project communication.

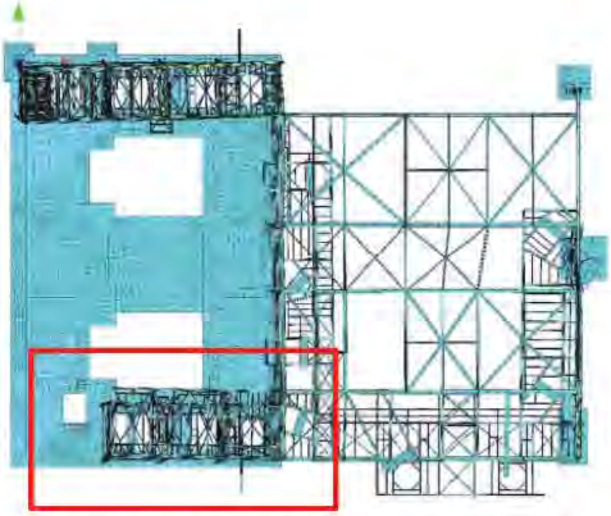

Figure 6. Analysis of the entire system with deformations

6 Conclusions and Proposal for Future Code Generations

Structural reliability is often treated in a dogmatic way. In standardization committees, experts discuss even minor changes to partial safety factors, even though many basic variables, especially e.g. model uncertainties, can only be modelled inaccurately. Considering the fact, that only a negligibly small number of failures happens due to the combination of extremely high actions and insufficient resistances, this discussion seems unnecessary in terms of structural safety.

It is well-documented that structural failure is mostly a consequence of human error. As shown in the simplified examples, common human errors may lead to deficits in structural reliability which cannot be covered by any partial safety factor. Further, recent examples of human errors that would have slipped undetected without independent design review have been presented to verify that human errors happen despite all quality control measures inside a design office. After all, this paper intends to put further attention on development and application of adequate design review procedures and shows that the often-stated argument of partial safety factors subconsciously accounting for human error is false.

It becomes clear that structural integrity and safety is much more related to proper design review procedures than it is to structural reliability. It is the goal of this paper to achieve a shift in the discussions about structural safety from focussing on safety factors to reliability control regarding human error. As the examples show, this can only be achieved by implementing technical as well as economical independent design review strategies.

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Der Einfluss menschlicher Fehler auf die Tragwerkszuverlässigkeit

Der Schutz des menschlichen Lebens und körperliche Unversehrtheit sind grundlegende Menschenrechte und folglich ein fundamentaler Bestandteil der Gesetzgebung eines Staates. Der vorliegende Artikel befasst sich mit den Ursachen in Fällen von Tragwerksversagen und den Möglichkeiten, um dies zu verhindern.

Jede Bemessung legt Teilsicherheitsbeiwerte zu Grunde, die auf probabilistischen Berechnungen oder empirischen Größen beruhen. Menschliche Fehlhandlungen im Planungs- und Ausführungsprozess lassen sich hierbei jedoch, wie oftmals fälschlicherweise angenommen wird, mathematisch durch die Teilsicherheitsbeiwerte nicht einheitlich berücksichtigen. Gründe für menschliche Fehlhandlungen äußern sich größtenteils infolge kultureller und systematischer Ursachen. Um diesen Fehlerquellen entgegenzuwirken, ist es erforderlich, ein Qualitätsmanagementsystem (QMS) bzw. ein Zuverlässigkeitsmanagementsystem (RMS) einzusetzen, das im besten Fall den gesamten Planungs- wie auch Ausführungsprozess betrachtet.

Die Beziehung zwischen menschlichem Versagen und Tragwerksversagen wird zunächst anhand von zwei fiktiven Beispielen veranschaulicht. Einerseits wird ein Ausführungsfehler erläutert, bei dem die obere und die untere Bewehrung einer Stahlbetonplatte vertauscht wurden. Andererseits wird am Beispiel einer Stahlstütze gezeigt, welche Auswirkung eine Veränderung des statischen Systems haben kann. Abschließend zeigen drei reale Beispiele, welche Folgen ein falscher Bewehrungseinbau, die Missachtung von Belastungsfällen und die Vernachlässigung von Bauzuständen haben können. In jedem Fall wird der theoretische Wert des Zuverlässigkeitsindexes mit dem durch die menschlichen Fehlhandlungen vorhandenen verglichen. Dadurch soll veranschaulicht werden, dass ein menschliches Versagen auch durch sehr hohe und ineffiziente Teilsicherheitsfaktoren nicht abzudecken ist. Noch kritischer ist es, wenn die menschlichen Fehlhandlungen den auftretenden Versagensmodus verändert. Hiermit wird gezeigt, dass die Standsicherheit viel mehr von der bautechnischen Prüfung als von dem rechnerischen Wert der Zuverlässigkeit abhängt.

Influence of the Design Review Process on the Structural Design Engineer due to Human Factors

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Abstract

It is common sense, that human error is the major cause for structural collapse [1]. Design review is the most effective way to rid human errors out of the design process and thus most societies have procedures for the design review installed. These systems work differently, e.g. preventive or repressive, and consequently affect the involved parties differently.

In this paper, the effect of different design review systems on the engineer as an individual will be assessed by addressing human factors that influence design decisions. The paper will focus on the structural design engineer, the effects on other included parties will be assessed in following studies.

The goal is to provide a better understanding of the impact of the design review procedure on the individual. Human factors affect the design engineer subconsciously and influence the decision-making in a significant way. Awareness of these factors and the corresponding influence due to the design review system will improve the design outcome and the relationship of design engineer and design review engineer.

Keywords: human factors, design checking, supervision, failure causes, prevention

1 Introduction

The protection of human life and its physical integrity are fundamental human rights and consequently a crucial part of a nation's legal framework. To provide the utmost safety without making structures inefficient and unaffordable, different approaches for building control have been chosen by various countries [2]. In design, sufficient structural integrity is thought to be achieved through application of partial safety factors which are deemed to define the necessary margin between the design values of the actions and the design value of resistances. Safety factors are derived from prediction models and stochastic assessment, i.e. the design problem is formulated under uncertainty to account for variations in so-called (random) basic variables such as load magnitude, material strengths, geometrical deviations, uncertainty in the prediction models etc. From there, the reliability of a structural component can be determined by use of advanced algorithms (see [2]and [4] for further information). Note, that reliability is a characteristic property of a member that can be compared to the target reliability which is given in design codes (e.g. in Europe EN 1990 [5]). From the reliability analyses, deterministic approaches to account for the reliability of structural members are derived, with the concept based on partial safety factors being the most widely used one. In other words, partial safety factors account for uncertainty related to extreme actions and material properties as well as geometric properties falling below the reference levels. This explains why the number of structural failures due to extreme actions in combination with significant deficits in structural strengths is fairly low (see section 3). However, probabilistic models describe uncertainty under a set of pre-set conditions. Reasonable deviations from the nominal values applied in design are thought to be included in this uncertainty.

Human errors, however, likely lead to entirely new conditions as these are not covered by the mentioned probabilistic models. Thus, the academic structural system "without errors" requires a totally different verification than the real-world structural system "subjected to errors", i.e. the partial safety factors commonly applied in design do not account for human errors. In a conventional engineering assessment, the physical cause for a failure is derived and assessed with an emphasis on the correct application of design codes. It is however more crucial to be aware of possible fields of human errors and the required mechanisms and methods to avoid them since structural failure happens mostly due to human errors (see section 2). These mechanisms and methods have to be known and understood to avoid human errors.

2 Failure Causes

Structural failures have been documented since the recording of events. In ancient times, structural failures were considered to be acts of god since the events were often disastrous and unforeseeable. Nowadays, structural analysis allows for scientific verification of the structural integrity. However, structural failures still occur. Researching the structural failures in the past shows that the causes can primarily be categorized by:

A Failures due to unforeseeably high actions or insufficient (aleatory) structural strength

B Failures due to human error

Cause A refers to structures with appropriate design according to the valid design standards and codes at the time of construction. Failure then occurred due to extremely high loads which exceed the characteristic value of the actions according to the appropriate codes in conjunction with insufficient material strength. Failure due to this cause is unlikely and normally covered by safety concepts (such as partial safety factors) as mentioned in the introduction.

Cause B is responsible for failure in almost every case – failure does commonly include human error. Table 1 shows the typical causes for structural failures in a more detailed way. The table is based on the findings of [6]. In the corresponding analysis, only 6% of failures were found to be caused by unforeseeable events. The by far larger portion of failures are caused by human errors that ideally could have been prevented by proper measures.

Table 1 Causes and distribution of structural failures according to [6] (published in [7])

Cause of Failure	% of total damages
Ignorance, Carelessness	37%
Insufficient Knowledge	27%
Underestimation of Influences	14%
Forgetfulness and Mistakes	10%
Unjustified Reliance on Others	6%
Objectively Unknown Situations and Influences	6%

3 Human Errors

3.1 Classification

According to [8] and [9], human error can be classified into three basic categories: mistakes, slips and lapses. They can be differentiated depending on sequence and execution of the relevant process [10]. A slip is defined as incorrect execution of correct sequences of actions, while a mistake is a correct execution in incorrect sequence of actions. A lapse is defined as omitted or left out actions.

Additionally, human errors can be defined as manifest and latent [10]. While manifest errors are committed by people with direct contact to the structure, such as construction workers, latent errors are committed by designers and such. The latter cannot check the consequences of their work immediately – a design error may only be found once the structure is under execution. Manifest errors will reveal themselves as errors immediately.

According to [11], human errors can also be categorized according to the information processing within the human mind.

The differentiation can be drawn between three modes: knowledge-based, rule-based, and skill-based.

- The knowledge-based errors occur despite the utmost diligence due to incomplete or inaccurate understanding of the designed system and its materials and is often fostered by overconfidence and people's tendency to prefer information which confirms one's preconceptions.
- The rule-based mode refers to errors that occur due to blind application of rules by e.g. using a wrong rule or the right rule incorrectly. The psychological reason is for these types of errors is the faster achievement of the design results and the lower effort on a conscious level.
- The skill-based mode refers mostly to slips that happen due to strong routine in solving design tasks (e.g. typos).

3.2 Error Causes

Human error can occur at every stage of planning and construction, not only during design. Therefore, it has to be taken into account and avoided during design and execution as well as during service. According to [1], human error is divided almost evenly between design and construction phases. Additionally, the often referred to "calculation flaw" has proven to be only a minor reason for a serious design error. Failure does not necessarily happen within the first years in the service life of a structure, even though it is more likely.

To be able to identify possible human error, one needs to be aware that human errors of the types provided in Table 1 do not happen without a reason. The commonly mentioned reasons according [12] are:

- Time pressure, too low engineering fees
- Pressure to minimize the costs of the structure to be built
- Insufficient coordination of the design
- Black-box-type use of design software
- Lack of detailing
- Large number of new standards and design rules

It becomes clear that human error, and consequently structural failure, is caused to a large extent by systematic and cultural issues (pay grids, time pressure).

The two main causes (A and B, see section 2) for structural failure must be tackled efficiently. While the cause A – failure due to unforeseeably high actions or insufficient structural strength – can be counteracted by design concepts in structural codes, cause B – human error – requires an organisational set of measures, referred to as **Q**uality or **R**eliability **M**anagement **S**ystem (QMS or RMS). Possible QMS or RMS systems may be provided in design codes, such as EN 1990 [5], Annex B. The presented sets of measures mostly include design supervision and site inspections, which have proven to be effective methods to identify and prevent human errors (see [12]). While the aforementioned cultural issues need to be assessed by politicians and legal experts, the fulfilment of due diligence and the correct application of an RMS need to be assessed by engineers.

The actual reasons for human errors are manifold and can be found on different levels of the design organisation, such as the personal level of the design individual or the management level of the organisation.

Despite the common categorization, the authors suggest only three categories:

- **Executive Management**

This category refers to all errors that could have been prevented by proper management within the organisation, such as errors related to staff rotation, overestimation of technical skills of the project team, poor coordination of tasks or lack of quality control. Also work overload of the design engineers should be considered in this category due to poor management in the assignment of tasks. Additionally, lack of motivation or boredom of the design staff should be assessed in this category since a justified pay grid as much as the right positioning of the design tasks is within the responsibility of the management. Another important factor within the management's responsibility is communication. The management has to make sure that communication within the project teams is successful. The communication with other parties within the project requires excellent project management, mainly by the project lead, to make sure that individuals as well as software can communicate successfully.

- **Personal**

This category refers to the error causes within the individual, mainly psychological and sociological reasons, such as personal stress due to interpersonal conflicts or excessive personal ambitions. Other reasons in this category may reflect personality flaws such as ignorance, indolence or greed. Certain human traits will contribute as well, such as intentional withholding of information to avoid consequences or attempts of solving the issues without further (and required) assistance. Especially the latter is often a result of a highly stressed job market and the misconception of admittance of the need of assistance as a sign of weakness and underperformance. Another important aspect is the strong development of design software in combination with changes in the education of engineers. There is a strong tendency, especially among recent graduates, to overly confide in engineering software. The reasons are a generally deeper relationship among young people ("digital natives") to software and technology, as well as a shift in the education away from the "hard" subjects (such as structural mechanics) to software application.

- **Imposed externally and culturally**

This category refers to all causes that are imposed on the organization from a political or societal level, such as new, more complex design codes, financial pressure due to flawed budgeting, or high workload due to e.g. low interest rates. However, it is the management's responsibility to organise the project as best as possible in reaction to the imposed influences. As an example, imagine a large public project that is assigned to an engineering company for the structural design. The company has to fulfill the design task within a certain time frame, so that enough staff has to be on the job, often requiring the hiring of further staff. Now it is common, that public budgets require extension over several years, possibly leading to a delay in the project over large periods of time. This will require the design company to take on further projects to provide enough work for all staff. At some, often unknown, point in time, the work on the large public project will continue, usually without much notice, and then under an increased time pressure. In this case, the management has only limited options to react, especially considering the legislation for protection of employment. Further externally imposed possible sources of human error include the growing extent and complexity of design codes. In Europe, this is mostly caused by the process of European integration and the development of the Eurocodes which multiplied the number of pages of the Eurocode series several times compared to the relevant previous national code generation (e.g. the DIN code series in Germany).

From these thoughts, the large responsibility in the avoidance of human error of the individual, the executive management of the design organisation, as well as the governing body becomes clear.

4 Reliability Management Systems to Counteract Human Error

4.1 General

To counteract human errors, most countries have legally implemented strategies (reliability management systems (RMS)). These strategies differ in many aspects (see sections 4.2 and 4.3) but commonly use design checking as powerful tool against errors. In structural design, this leads to the definition of two major engineering roles: the design engineer (whose work will be checked) and the design review engineer (who will perform the design check).

The roles of the structural design engineer (DE) and the design review engineer (DR) are defined in the RMS. RMS represent the state building control during design and execution of a project. Thus, RMS can be seen as the defence line against human error. However, it is the last line of defence – ideally human error is already tackled before the design documents leave the design office and buildings go into execution.

RMS are different internationally. The respective state administrates this responsibility by granting building permits. The RMS is consequently linked to the building permit. Every state has different legislation so that the RMS exhibit minor or major differences. However, the RMS can be divided into two general types (see 4.2 and 4.3) depending on the main approach to the avoidance of structural failures by identification and avoidance of human error.

Notwithstanding, it becomes evident that not all the previously mentioned error causes, namely the personal and management causes, are covered by the RMS.

4.2 Repressive System

A typical version of a repressive system is explained by the example of the system applied in France. For the issuing of a building permit, the building authorities only check zoning aspects and the building master plan. Structural integrity is within the responsibility of the parties involved with the construction: architect, contractor, and owner who are legally obligated to build up to the relevant codes. However, fulfilment is not to be checked by the authorities. The parties are also legally obligated to take out insurance policies to cover risks associated with the construction.

The advantage of this system is the financial safety in case of failure and damages since the insurance will cover possible claims. However, disadvantages are substantial – reliability management does not happen to prevent failure in the first place and the structural cost increases significantly due to the cost of the insurance policies. Design reviewing and site inspections are only performed if an involved party specifically requires these, e.g. the insurance might grant better policy conditions for the owner if design reviewing is performed. Compared to the above identified causes for structural failure, the following must be stated:

Cause A (unforeseeably high actions or insufficient structural strength) and B (human error) are not necessarily covered since there is not a legal requirement to review the design before the building permit is granted. A building permit can be obtained without design and execution supervision. However, design and execution supervision often happens under private law.

4.3 Preventive System

Contrary to the repressive system, the preventive system tries to avoid structural failure in general by consequent design supervision, already before the permit is granted, and on-site inspections for checking the execution. A typical example for a preventive system is the system applied in Germany, presented in Figure 1. In this system, a full design review by a highly qualified and chartered design review engineer has to be performed and reported to the building authorities before the building permit is granted. During construction, the design review engineer is responsible for checking all the relevant design drawings as well as for performing sample inspections of the execution (e.g. reinforcement in situ). The disadvantages of this system lie within the possibly larger inertia in the design and execution phase as an additional, economically independent party is involved. But this additional player introduces advantages into the design and execution process as he provides the prevention of failures and cost-efficiency since additional insurance policies are not required.

Compared to the identified causes for structural failure, the following must be stated:

The first and second cause are covered since there is a legal requirement to check the design before the building permit is granted, e.g. in Germany the detailed report of the design check is a requirement for granting a permit. A building permit cannot be obtained without design and execution supervision. After completion, the design review engineer has to provide another report.

The preventive system is sometimes criticized for the possible relying of the design engineer on the design review engineer leading to a flawed design in hope the design review engineer will find mistakes. From the authors' experience as consulting engineers, however, this is generally not the case because the design engineer understands the liability issue (the liability lies with the design engineer, not the design review engineer) and a flawed design will harm the firm's reputation. Additionally, the design review engineer does not solve possible mistakes for the design engineer, he will require additional documentation and verification. This again leads to more effort. Thus, relying on "design aid" by the design review engineer will only cause inefficient design and disadvantages for the design engineer.

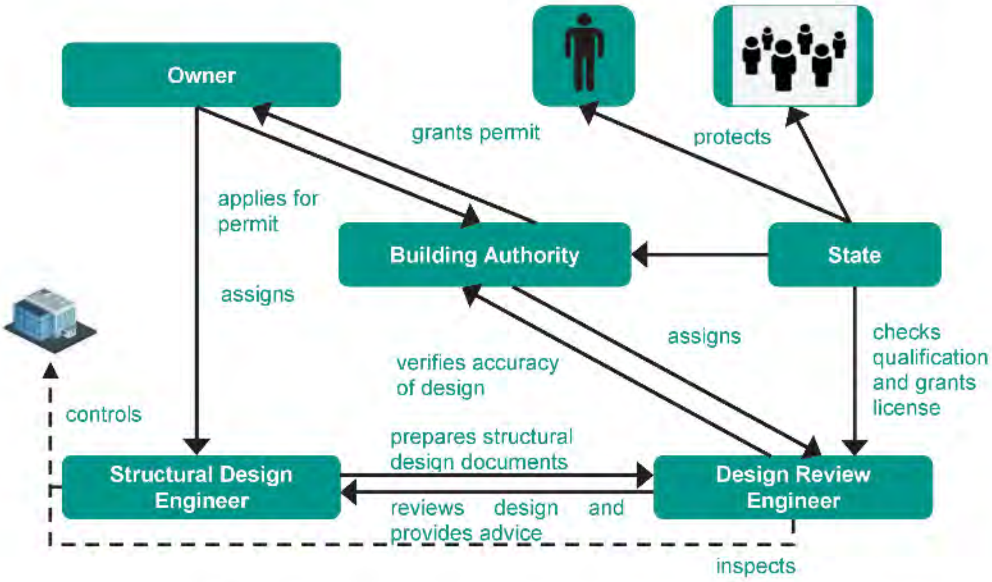

Figure 1. Preventive system by the example of the German system

4.4 The Role of the DE in an RMS

In the preventive system (see section 4.3), the DE is the responsible engineer for the outcome of the project. If structural failures occur and errors in the design are identified, the actual design engineer who performed the design will be responsible – not the owner of the design company, not necessarily the person who signed off on the design. If the damage is only financial, the design company's insurance will step in, with most likely severe consequences for the DE who performed the design in terms of career opportunities. This puts the DE under permanent pressure and leads to on-going self-checks during the work process.

Additionally, the DE is responsible not only for structural integrity but also for all aspects of serviceability. While the DR, in his role as representative of the building authority, may only address issues regarding structural integrity, the DE will be held responsible for every issue related to the structure. Since damages and failures in terms of serviceability (cracks, deformations etc.) are far more likely to occur than structural failures, the pressure is higher for the DE.

The DE is part of the design organisation and thus the causes of human error should efficiently be addressed within the organisation.

4.5 Criticism

The RMS described in sections 4.2 and 4.3 provide a framework to counteract human error by generating the necessity of design checking. However, they do not provide detailed guidance on how to avoid human error regarding the human factors mentioned in section 3.

The human errors are undeniably orchestrated by human factors which are fostered by various mechanisms. While the common RMS focus on the identification and finding of human errors in the design documents and execution, thus not preventing human errors but detecting and fixing them, prevention of human errors in terms of reduction of the likelihood of their occurrence should be a major part of an RMS.

5 Suggested methods of counteracting human error on the side of the DE

5.1 General

It is sometimes mentioned [10] that human error can be incorporated into the design procedures by e.g. assuming the appropriate value of probability of failure. This seems impossible since human error changes the entire limit state. Just imagine a column under compression. The engineer may have estimated the buckling length incorrectly due to a misunderstanding of the support situations. The failure mode of the column then may change from compression failure on cross-sectional level to buckling. No safety factor, no matter the quantity, will solve this issue and provide a safe and efficient solution. Thus, human error must be covered by useful measures in terms of quality control.

Based on the findings of the previous section, RMS should be extended to reduce the probability of human errors instead of focussing on their identification. In the following sections ways of enhancing the avoidance rate of human errors will be explained. Note, that these ways will focus on the DE since avoidance of human errors before they occur only affects the DE, not the DR.

5.2 RMS inside the organisation

As mentioned in section 3.2, the management of a design organisation plays a major part in avoiding human errors. Besides the approaches to limiting pressure on the DE, the design organisation should provide a framework for training and education of the DE. Most design organisations provide means for further training and education of the DE. As on-going training is a requirement for members of the engineering chambers, it is not a legal requirement for every DE. Thus, the management of the design organisation needs to set a mandatory requirement for its DE to pursue further training and must provide sufficient amounts of time. As simple as this sounds, especially smaller design organisations will face severe issues in substituting the loss of man power during training sessions.

5.3 Error management system

Another opportunity for design organisations is an open way of dealing with errors by assessing and publishing them internally, in e.g. intranet sources as well as internal workshops. Every error is also an opportunity for growth and lessons learned and should be treated accordingly.

Some states have established routines for the (anonymous) publication of design errors, such as CROSS ("Confidential reporting on Structural Safety") in the UK [13]. This allows for a steady improvement of the RMS strategies and for a generally better understanding of human error in structural design tasks.

5.4 Cultural Change

However, the major aspect of avoiding human error by the DE should be an effective way to tackle the personal error causes mentioned in section 3.2 which are mostly related to pressure being subjected to the DE. In a fast moving industry with large budgets at stake, pressure of course cannot be avoided. However, it can be limited and taken of the individual's shoulders. The major aspect here should be a cultural change – away from a competition (price)-driven market to a quality-driven one. Away from trickling down the responsibilities from top to bottom, towards strong leadership that protects the DE on lower hierarchy levels. While smaller design organisations with flat hierarchy levels, often consisting of the owner and a handful engineers, have shown to fulfil this goal, larger organisations tend to have a wider spread of responsibility. Pressure thus can only be reduced if large as well as small design organisations can work in a supportive environment in terms of fair compensation and market share.

As far as price-driven markets should act of course, some countries tackle this issue by providing fee grids for engineering services. The public sector is legally required to keep to these grids while the private sector can still negotiate freely. Investigations by several engineering chambers in Germany, as well as the authors' practical experience, shows that the private sector will almost always try to undermine the pay grids. This can be extremely frustrating for the design organisations, especially keeping in mind that it is not typical in other lines of work that have pay grids (physicians, lawyers). To be able to work efficiently, design organisations are forced to take on larger work loads that will inevitably lead to higher pressure on the DE. This is where change must happen. But it can only be achieved by industry-wide changes in the thinking of leaders, similar to a code of ethics to quote according to the pay grids to be able to provide good compensation for the DE to reduce pressure and stress and increase societal value of the occupation.

6 Conclusions

It is common sense that human error is the main reason for structural damage and failure. Most states impose a reliability management system (RMS) to avoid human error. However, further causes for human error, rooted in personal causes of the individual and management of the design organisation, are not covered by the RMS. This paper pointed out that these more effective avoidance of human error requires the individual and, especially, the management to act. Suggestions for improvements are presented, such as error management systems and transparent pay grids. Further a cultural change within the engineering community and society is discussed and derived as a main factor on avoiding human error.

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Die bautechnische Prüfung als Instrument zur Vermeidung menschlichen Versagens – ein kooperativer Ansatz

Das oberste Schutzziel eines Staates ist der Schutz des menschlichen Lebens und die körperliche Unversehrtheit seiner Bürger, und damit ist er ein fundamentaler Bestandteil der Gesetzgebung. Bauaufsichtliche Aufgaben, wie die hoheitliche bautechnische Prüfung, dienen der Erfüllung dieses Schutzziels. Der vorliegende Artikel befasst sich mit einem kooperativen Ansatz der bautechnischen Prüfung.

Jede Bemessung legt Teilsicherheitsbeiwerte zu Grunde, die auf probabilistischen Analysen beruhen. Diese haben den Zweck, die Streuung der Materialparameter, die Auftretenswahrscheinlichkeit bestimmter Lastfälle, etc. zu erfassen und so ein ausreichendes Zuverlässigkeitsniveau zu gewährleisten. Menschliche Fehlhandlungen im Planungs- und Ausführungsprozess lassen sich hierbei jedoch nicht einheitlich berücksichtigen.

Studien haben gezeigt, dass lediglich in ca. 6 % aller Fälle objektiv unvorhersehbare Ereignisse zu einem Tragwerksversagen geführt haben, der restliche Anteil resultierte aus menschlichen Fehlhandlungen. Als effektiv zur Vermeidung von menschlichen Fehlhandlungen hat sich die bautechnische Prüfung erwiesen.

Ein effizientes System der bautechnischen Prüfung kann nur mittels unabhängiger vorbeugender Kontrollen durch eine zweite Instanz erfolgen (4-Augen-Prinzip), um Fehler zu identifizieren und zu beheben, bevor deren Auswirkungen den Projektablauf negativ beeinflussen. Als Beispiel wird hierfür der Prüfstatiker in Deutschland angeführt, dessen Aufgabe es ist, die Arbeit des Tragwerksplaners zu kontrollieren und die Bauüberwachung durchzuführen.

Menschliche Faktoren beeinflussen die Effektivität der bautechnischen Prüfungen. Um auf menschliche Faktoren besser einzugehen und damit die Effektivität der bautechnischen Prüfung weiter zu verbessern, kann das System erweitert werden. Zur Erweiterung des Zuverlässigkeitsmanagementsystems (RMS) werden in diesem Beitrag mögliche Lösungsansätze wie stetige Fortbildungsmaßnahmen, ein internes Fehlermanagementsystem (per Intranet oder internen Workshops) sowie ein notwendiger kultureller Wandel analysiert. Ein Fehlermanagementsystem soll bewirken, dass interne Fehler offen kommuniziert werden und aus diesen ein Lerneffekt gewonnen wird.

Der wichtigste Punkt aber wäre ein kultureller Wandel weg vom preisgesteuerten Markt hin zum qualitätsorientierten Markt in der Baubranche. Hierzu bedarf es transparenter und einheitlicher Honorare für Ingenieurdienstleistungen, vor allem auch bei privaten Aufträgen.

Des Weiteren muss eine Kooperation aller Projektbeteiligten stattfinden, um ein gegenseitiges Verständnis der individuellen Aufgaben und Sichtweisen zu gewinnen und somit Fehler zu minimieren. So soll ein interdisziplinärer Projekterfolg mit Vorteilen für alle Projektbeteiligten erzielt werden.

Als Vorschlag wird an einem Beispiel gezeigt, dass es in Deutschland sinnvoll wäre, den Prüfingenieur bereits in frühen Projektphasen miteinzubeziehen, um so von seiner hohen Qualifikation zu profitieren und folglich ein qualitativ noch hochwertigeres Endergebnis zu erzielen.

Challenges towards Design Review due to Cultural and Human Factors

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1 Abstract

Design review has proven effective to avoid human errors in the design process. Since human error is the major cause for structural collapse [1], most countries have implemented procedures for design review in their building legislation. These systems represent the lived building culture in each state and thus work differently.

Within the European harmonization process, challenges regarding the integration of different building cultures have been discovered. These cultural challenges affect structural safety in a wide array of topics, e.g. technical approval of building products.

In this paper, the effect of differences in the building culture and the way they affect structural safety will be investigated. Furthermore, the effect on the individual due to human factors will be examined and assessed.

The goal is to provide a better understanding of the impact of cultural differences on the design review procedure and on the individual.

Keywords: cultural differences, human factors, design review, structural safety

2 Introduction

The protection of human life and its physical integrity are fundamental human rights and consequently a crucial part of a nation's legal framework. To provide the utmost safety without making structures inefficient and unaffordable, different approaches for building control have been developed and implemented by various countries [2]. In design, sufficient structural integrity is commonly thought to be achieved through application of safety factors, which are deemed to define the necessary margin between the design values of the actions and the design value of resistances. Safety factors are determined from prediction models and stochastic assessment, i.e. the design problem is formulated stochastically (under uncertainty) to account for variations in so-called (random) basic variables such as material strengths, geometrical deviations, uncertainty in the prediction models etc. From there, the reliability of a structural component can be determined by use of advanced algorithms (see [2]and [4] for further information). Note, that reliability is purely a characteristic of a member that can be compared to the target reliability which is given in design codes (e.g. in Europe EN 1990 [5]). From the reliability analyses, deterministic approaches to account for the reliability of structural members are derived, with the semi-probabilistic concept being the most widely used. In other words, partial safety factors account for uncertainty related to extreme actions and material properties as well as geometric properties falling below the reference levels. This explains why the number of structural failures due to extreme actions in combination with significant deficits in structural strengths is fairly low (see section 3). However, probabilistic models describe uncertainty under a set of pre-set conditions. Reasonable deviations from the nominal values applied in design are thought to be included in this uncertainty.

Human errors, however, likely lead to entirely new conditions as these are not covered by the mentioned probabilistic models. Thus, the academic structural system "without human errors or design flaws" requires a totally different verification than the real-world structural system "subjected to errors", i.e. the partial safety factors commonly applied in design do not account for human errors. In a conventional engineering assessment, the physical cause for a failure is derived and assessed with an emphasis on the correct application of design codes. It is however more crucial to be aware of possible fields of human errors and the required mechanisms and methods to avoid them since structural failure happens mostly due to human errors (see section 3). These mechanisms and methods have to be known and understood to avoid human errors.

Having this in mind, it become obvious that fulfilling the most noble task of a society, i.e. the interception of undue risks, reaches far beyond mathematical or physical models. Especially the human factor makes it nearly impossible to tackle it by relaying on purely academically justified reliability strategies only, as there is no general and strong probability model of human´s susceptibility to errors.

3 Failure Causes

Structural failures have been documented since the recording of events. In ancient times, structural failures were considered to be acts of god since the events were often disastrous and unforeseeable. Nowadays, structural analysis allows for scientific verification of the structural integrity. However, structural failures still occur. Researching the structural failures in the past shows that the causes can primarily be categorized by:

A Failures due to unforeseeably high actions or insufficient (aleatory) structural strength

B Failures due to human error

Cause A refers to structures with appropriate design according to the valid design standards and codes at the time of construction. Failure then occurred due to extremely high loads which exceed the characteristic value of the actions according to the appropriate codes in conjunction with insufficient material strength. Failure due to this cause is unlikely and normally covered by safety concepts (such as partial safety factors) as mentioned in the introduction.

Cause B is responsible for failure in almost every case – failure does commonly include human error. Table 1 shows the typical causes for structural failures in a more detailed way. The table is based on the findings of [6]. In the corresponding analysis, only 6% of failures were found to be caused by unforeseeable events. The by far larger portion of failures are caused by human errors that ideally could have been prevented by proper measures.

Table 1. Causes and distribution of structural failures according to [6] (published in [7])

Cause of Failure	**% of total damages**
Ignorance, Carelessness	37%
Insufficient Knowledge	27%
Underestimation of Influences	14%
Forgetfulness and Mistakes	10%
Unjustified Reliance on Others	6%
Objectively Unknown Situations and Influences	6%

4 Human Errors

4.1 Classification

According to [8] and [9], human error can be classified into three basic categories: mistakes, slips and lapses. They can be differentiated depending on sequence and execution of the relevant process [10]. A slip is defined as incorrect execution of correct sequences of actions, while a mistake is a correct execution in incorrect sequence of actions. A lapse is defined as omitted or left out actions.

Additionally, human errors can be defined as manifest and latent [10]. While manifest errors are committed by people with direct contact to the structure, such as construction workers, latent errors are committed by designers and such. The latter cannot check the consequences of their work immediately – a design error may only be found once the structure is under execution. Manifest errors will reveal themselves as errors immediately.

According to [11], human errors can also be categorized according to the information processing within the human mind.

The differentiation can be drawn between three modes: knowledge-based, rule-based, and skill-based errors.

- The knowledge-based errors occur despite the utmost diligence due to incomplete or inaccurate understanding of the designed system and its materials and is often fostered by overconfidence and people's tendency to prefer information which confirms one's preconceptions.
- The rule-based mode refers to errors that occur due to blind application of rules by e.g. using a wrong rule or the right rule incorrectly. The psychological reason is for these types of errors is the faster achievement of the design results and the lower effort on a conscious level.
- The skill-based mode refers mostly to slips that happen due to strong routine in solving design tasks (e.g. typos).

4.2 Error Causes

Human error can occur at every stage of planning and construction, not only during design. Therefore, it has to be taken into account and avoided during design and execution as well as during service. According to [1], human error is divided almost evenly between design and construction phases. Additionally, the often referred to "calculation flaw" has proven to be only a minor reason for a serious design error. Failure does not necessarily happen within the first years in the service life of a structure, even though it is more likely.

To be able to identify possible human error, one needs to be aware that human errors of the types provided in Table 1 do not happen without a reason. The commonly mentioned reasons according [12] are:

- Time pressure, too low engineering fees
- Pressure to minimize the costs of the structure to be built
- Insufficient coordination of the design
- Black-box-type use of design software
- Lack of detailing
- Large number of new standards and design rules

It becomes clear that human error, and consequently structural failure, is caused to a large extent by systematic and cultural issues (pay grids, time pressure).

The two main causes (A and B, see section 2) for structural failure must be tackled efficiently. While the cause A – failure due to unforeseeably high actions or insufficient structural strength – can be counteracted by design concepts in structural codes, cause B – human error – requires an organisational set of measures, referred to as **Q**uality or **R**eliability **M**anagement **S**ystem (QMS or RMS). Possible QMS or RMS systems may be provided in design codes, such as EN 1990 [5], Annex B, even if this is not the suitable spot for dealing with this issue, as, by nature, QMS or RMS and design rules are two very different sides of the medal (see above).

The presented sets of measures mostly include design supervision and site inspections, which have proven to be effective methods to identify and prevent human errors (see [12]). While the aforementioned cultural issues need to be assessed by politicians and legal experts, the fulfilment of due diligence and the correct application of an RMS need to be assessed by engineers.

The actual reasons for human errors are manifold and can be found on different levels of the design organisation, such as the personal level of the design individual or the management level of the organisation.

Despite the common categorization, the authors suggest only three categories:

- **Executive Management**

This category refers to all errors that could have been prevented by proper management within the organisation, such as errors related to staff rotation, overestimation of technical skills of the project team, poor coordination of tasks or lack of quality control. Also, work overload of the design engineers should be considered in this category due to poor management in the assignment of tasks. Additionally, lack of motivation or boredom of the design staff should be assessed in this category since a justified pay grid as much as the right positioning of the design tasks is within the responsibility of the management. Another important factor within the management's responsibility is communication. The management has to make sure that communication within the project teams is successful. The communication with other parties within the project requires excellent project management, mainly by the project lead, to make sure that individuals as well as software can communicate successfully.

- **Personal**

This category refers to the error causes within the individual, mainly psychological and sociological reasons, such as personal stress due to interpersonal conflicts or excessive personal ambitions. Other reasons in this category may reflect personality flaws such as ignorance, indolence or greed. Certain human traits will contribute as well, such as intentional withholding of information to avoid consequences or attempts of solving the issues without further (and required) assistance. Especially the latter is often a result of a highly stressed job market and the misconception of admittance of the need of assistance as a sign of weakness and underperformance. Another important aspect is the strong development of design software in combination with changes in the education of engineers. There is a strong tendency, especially among recent graduates, to overly confide in engineering software. The reasons are a generally deeper relationship among young people ("digital natives") to software and technology, as well as a shift in the education away from the "hard" subjects (such as structural mechanics) to software application.

- **Imposed externally and culturally**

This category refers to all causes that are imposed on the organization from a political or societal level, such as new, more complex design codes, financial pressure due to flawed budgeting, or high workload due to e.g. low interest rates. However, it is the management's responsibility to organise the project as best as possible in reaction to the imposed influences. As an example, imagine a large public project that is assigned to an engineering company for the structural design. The company has to fulfill the design task within a certain time frame, so that enough staff has to be on the job, often requiring the hiring of further staff. Now it is common, that public budgets require extension over several years, possibly leading to a delay in the project over large periods of time. This will require the design company to take on further projects to provide enough work for all staff. At some, often unknown, point in time, the work on the large public project will continue, usually without much notice, and then under an increased time pressure. In this case, the management has only limited options to react, especially considering the legislation for protection of employment. Further externally imposed possible sources of human error include the growing extent and complexity of design codes. In Europe, this is mostly caused by the process of European integration and the development of the Eurocodes which multiplied the number of pages of the Eurocode series several times compared to the relevant previous national code generation (e.g. the DIN code series in Germany).

From these thoughts, the large responsibility in the avoidance of human error of the individual, the executive management of the design organisation, as well as the governing body becomes clear.

5 Reliability Management Systems to Counteract Human Error

5.1 General

To counteract human errors, most countries have legally implemented strategies (reliability management systems (RMS)). These strategies differ in many aspects (see sections 4.2 and 4.3) but commonly use design review as powerful tool against errors. In structural design, this leads to the definition of two major engineering roles: the design engineer (whose work will be checked) and the design review engineer (who will perform the design check). For detailed information about the roles it is referred to [13]and [14].

The roles of the structural design engineer (DE) and the design review engineer (DR) are defined in the RMS. RMS represent the state building control during design and execution of a project. Thus, RMS can be seen as the defence line against human error. However, it is the last line of defence – ideally human error is already tackled before the design documents leave the design office and buildings go into execution.

RMS are different internationally. The respective state administrates this responsibility by granting building permits. The RMS is consequently linked to the building permit. Every state has different legislation so that the RMS exhibit minor or major differences. However, the RMS can be divided into two general types (see 4.2 and 4.3) depending on the main approach to the avoidance of structural failures by identification and avoidance of human error.

Notwithstanding, it becomes evident that not all the previously mentioned error causes, namely the personal and management causes, are covered by the RMS.

Hier sollten wir noch einen Verweis auf die von Christian Klein ausgegrabene Literatur aus den Niederlanden zum Vergleich der unterschiedlichen Systeme einflechten. Das was da drin steht ist doch sehr interessant. Hänge eine Kopie an.

5.2 Repressive System

A typical version of a repressive system is explained by the example of the system applied in France. For the issuing of a building permit, the building authorities only check zoning aspects and the building master plan. Structural integrity is within the responsibility of the parties involved with the construction: architect, contractor, and owner who are legally obligated to build up to the relevant codes. However, fulfilment is not to be checked by the authorities. The parties are also legally obligated to take out insurance policies to cover risks associated with the construction.

The advantage of this system is the financial safety in case of failure and damages since the insurance will cover possible claims. However, disadvantages are substantial – reliability management does not happen to prevent failure in the first place and the structural cost increases significantly due to the cost of the insurance policies. Design reviewing and site inspections are only performed if an involved party specifically requires these, e.g. the insurance might grant better policy conditions for the owner if design reviewing is performed. Compared to the above identified causes for structural failure, the following must be stated:

Cause A (unforeseeably high actions or insufficient structural strength) and B (human error) are not necessarily covered since there is not a legal requirement to review the design before the building permit is granted. A building permit can be obtained without design and execution supervision. However, design and execution supervision often happens under private law.

5.3 Preventative System

Contrary to the repressive system, the preventative system tries to avoid structural failure in general by consequent design supervision, already before the permit is granted, and on-site inspections for checking the execution. A typical example for a preventative system is the system applied in Germany, presented in Figure 1. In this system, a full design review by a highly qualified and chartered design review engineer has to be performed and reported to the building authorities before the building permit is granted. During construction, the design review engineer is responsible for checking all the relevant design drawings as well as for performing sample inspections of the execution (e.g. reinforcement in situ). The disadvantages of this system lie within the possibly larger inertia in the design and execution phase as an additional, economically independent party is involved. But this additional player introduces advantages into the design and execution process as he provides the prevention of failures and cost-efficiency since additional insurance policies are not required.

Compared to the identified causes for structural failure, the following must be stated:

The first and second cause are covered since there is a legal requirement to check the design before the building permit is granted, e.g. in Germany the detailed report of the design check is a requirement for granting a permit. A building permit cannot be obtained without design and execution supervision. After completion, the design review engineer has to provide another report.

The preventative system is sometimes criticized for the possible relying of the design engineer on the design review engineer leading to a flawed design in hope the design review engineer will find mistakes. From the authors' experience as consulting engineers, however, this is generally not the case because the design engineer understands the liability issue (the liability lies with the design engineer, not the design review engineer) and a flawed design will harm the firm's reputation. Additionally, the design review engineer does not solve possible mistakes for the design engineer, he will require additional documentation and verification. This again leads to more effort. Thus, relying on "design aid" by the design review engineer will only cause inefficient design and disadvantages for the design engineer.

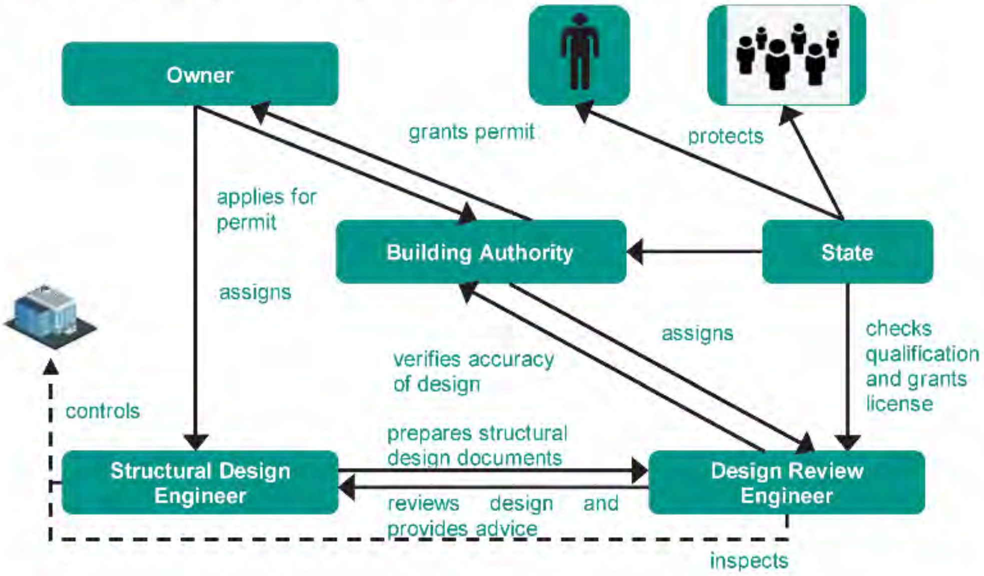

Figure 1. Preventative System of building control in Germany

6 Cultural Differences and Their Impact on the Error Causes

6.1 General

As mentioned before, structural safety falls within the responsibility of each society. Consequently, the strong differences may be discovered even in neighbouring states. Some states detail a repressive or preventative system, others do not explicitly detail a system but rely on the "lived" building culture. Since changes in the system of building control – during design, execution and maintenance – directly influences the actual safety level of structures in each state, this will also be different. However, structural failure is still a rare event, a lower level of safety will manifest over large periods of time. Numbers to prove a generally lower safety level are impossible to obtain, since a single large event overshadows the majority of non-catastrophic events.

Another important factor is the influence of design review on the building quality. Even if structural integrity, serviceability and durability are provided in a structural design, review will also be useful method for improvement in terms of execution, cost efficiency and related aspects.

6.2 Legal Aspects

Building control is part of a state's legal framework. Legal cultures are most defining for a society. Consider the American culture of large class actions, an aspect currently not present in Europe even though steps have been undertaken in this direction following the "diesel gate scandal". Also, the responsibility of the executive management is assessed considerably different from state to state: while in some states managers can receive substantial fines and prison sentences, while other states do not prosecute managers as strictly. As a recent example, the financial crisis left a variety of bank managers who exposed significant misbehaviour unemployed but with a golden handshake and without further prosecution. These aspects definitely influence the decision making of top management including the influence on human error.

Another important aspect with a strong influence on human error is competition. Some states support a strong market-oriented approach to produce maximum competition. This may have advantages for the client but will also increase the pressure on the individual. In the structural design context, i.e. the pressure on design engineer and design review engineer, which will cause more human error (see 4.2). Other countries attempt to circumvent this fact by introducing pay grids, e.g. the HOAI [16] in Germany for the design engineer and corresponding fixed fees for the design review engineer. What sounds like fantastic conditions for structural engineers to the disadvantage of the cients, as there is no real competition that leads to the cheapest fees, is currently being challenged on European level, since some countries interpret pay grids as an obstacle in entering the national market. When discussing this issue, it is worth to be mentioned that similar issues exist in other lines of business, e.g. lawyers and physicians also. The consequences of the pure market-oriented approach can be massive and not compatible with societies´ expectations, as recent examples show: due to increased competition and corresponding lower fees, the quality of work would become inferior, human error would occur more often and lead to existential damages. The international competition would also bring in service providers with generally lower quality standards but cheaper fees.

Further national and international legal aspects that influence the safety level of structures in a state and, consequently the error-proneness include the technical approval of construction products. In Europe, the requirements for the distribution of construction products across state borders have been reduced significantly [17]. Technical approval is no longer required for the sole purchase. However, the applicability of a product still has to be assessed against the basic requirements of structures - structural safety, fire protection, health protection, serviceability, sound protection, energy efficiency, and sustainability - leading to an increase in responsibility for the design engineer and design review engineer. Taking into account, that this equals a decision under economic pressure – the client expects the most efficient design – the design engineer faces decisions, which may exceed their competence, without another party to ask for assistance. It is important to note, that this issue can only be solved in a preventative system, where the design review engineer can step in before inappropriate products are used.

6.3 Personal Aspects

The state's political culture does not only influence the DE and DR, it also shapes the population's culture in terms of decision-making and perception of risk. As an example, consider the financial investment policies of Americans and Germans. While Americans traditionally invest large portions of their net worth in presumably high-risk products and stocks, Germans tend to invest their net worth in supposedly "safe" types of investments, e.g. real estate and bonds.

Further personal aspects include the handling of human error. Some states in general and companies exhibit a culture of open dealing with mistakes. The individual is invited to come forward if a mistake was made. Other cultures see human error as shameful and the individual is tempted to try to cover up possible error. As an example, again consider American and European culture. While an entrepreneur with a failed business is not frowned upon in America, in Europe a failed business is ultimately shameful and considered a personal defeat. A typical outcome of these cultural approaches are the very vivid start-up culture in America and the significantly smaller start-up scene in Europe.

7 Conclusions

It is common sense that human error is the main reason for structural damage and failure. Safety factors found in codes and standards do not cover human error, since they are only useful for covering mathematic and describable issues. Human error, however, has societal and personal causes and must be tackled by respective means. Thus, most states impose a reliability management system (RMS) to avoid human error. However, further causes for human error, rooted in personal causes of the individual and management of the design organisation, are not covered by the RMS. These causes are further influenced by cultural aspects relating to the respective society and individual. This paper pointed out that more effective avoidance of human error requires the individual and, especially, the management to act and to understand the cultural influences.

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Herausforderungen bei der bautechnischen Prüfung infolge von kulturellen und menschlichen Einflussfaktoren

Bei Tragwerksversagen sind in der Regel menschliche Fehlhandlungen die Hauptursache. Die bautechnische Prüfung hat sich in der Vergangenheit als effektives Mittel zur Vermeidung von menschlichen Fehlhandlungen erwiesen. Daher haben die meisten Staaten Verfahren der bautechnischen Prüfung in Form von Zuverlässigkeitsmanagementsystemen (RMS) eingeführt, welche die gelebte Baukultur in jedem Staat repräsentieren und daher unterschiedlich funktionieren. Dieser Artikel untersucht die Unterschiede in den Baukulturen und die resultierenden Auswirkungen auf die strukturelle Sicherheit. Aber auch die Auswirkungen durch menschliche Faktoren auf den Einzelnen werden untersucht und bewertet.

Menschliche Fehler lassen sich zunächst in offensichtliche (während der Bauausführung) und verborgene Fehler (während der Planung) differenzieren. Weitergehend ist eine Kategorisierung in drei unterschiedliche Fehler-Modi möglich:

- Wissensbasierter Modus: Fehler entstehen trotz größter Sorgfalt durch ein mangelndes Verständnis des Systems und seiner Materialien. Zudem erfolgt eine Begünstigung durch übermäßiges Selbstvertrauen.

- Regelbasierter Modus: Fehler entstehen durch die blinde Anwendung von Regeln infolge der Fehlanwendung richtiger Regeln oder der Anwendung falscher Regeln.

- Fähigkeitsbasierter Modus: Fehler entstehen durch starke Routine beim Lösen von Bemessungsaufgaben.

Allgemein können Fehler während jeder Planungsphase auftreten, und sie lassen sich oft zurückführen auf Zeitdruck, Kostendruck, mangelnde Planungskoordination, mangelndes Verständnis der Bemessungssoftware, ungenügende Detaillierung, große Normen- und Richtlinienzahl. Ein Großteil der Versagensursachen basiert jedoch auf systematischen und kulturellen Fragen. Daher werden die folgenden Ebenen als tatsächliche Gründe für menschliche Fehler aufgeführt:

- Die Geschäftsleitung kann eine schlechte Personaleinteilung vornehmen, die technischen Fähigkeiten des Projektteams überschätzen, Mängel in der Koordination und Mängel bei den Qualitätskontrollen aufweisen. Oftmals kann auch eine Arbeitsüberlastung des Personals entstehen, begleitet von einer mangelhaften Kommunikation des Projektmanagements.

- Auf personaler Ebene sind die Fehlerursachen auf das Individuum infolge psychologischer und sozialer Gründe zurückzuführen.

- Die dritte Ebene enthält äußerlich und kulturell aufgezwungene Ursachen, welche die Belastung der Organisation von politischer oder gesellschaftlicher Ebene sowie den wachsenden Umfang und die Komplexität von Designcodes umfassen.

Es soll vor allem darauf aufmerksam gemacht werden, dass tiefgründigere Ursachen für menschliche Fehlhandlungen, die in den persönlichen Eigenschaften sowie der Situation des Einzelnen und der Leitung der Planungsorganisation verwurzelt sind, nicht durch das Zuverlässigkeitsmanagementsystem (RMS) abgedeckt werden. Eine wirksamere Vermeidung von menschlichem Versagen verpflichtet das Individuum und die Geschäftsleitung zum Handeln und zum Verständnis der kulturellen Einflüsse.

Practical Examples of Successful Design Review

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1 Abstract

Human error is the major cause for structural collapse [1]. Design review is the most effective way to rid human errors out of the design process and thus most societies have implemented procedures for design review. Naturally, different systems come with different properties in terms of effectiveness and error-proneness.

This paper will provide practical examples of successful design review and will derive challenges and methods of counteraction during the design review process. Emphasis will be on realistic examples as a basis for a theoretical derivation of improved design review concepts.

Keywords: human error, design review

2 Introduction

When structural failure occurs, human error is commonly the main cause [1]. While failure related to uncertainty in material strength, load effects or flawed design models can be tackled by application of safety factors (see [1] and [4]) in the structural design calculations, human error requires completely different approaches. Due to their very nature, the safety factors defined in rules and regulations do not cover human error. This is a very common misconception [5]. To protect the society from the potentially catastrophic consequences of human error in the structural design, most nations have implemented methods for design checking and design review, which have been proven useful in the identification of human error (see [3], [4] and [6]). In this paper, the term "design checking" refers to a pure check of the structural design by another expert while "design review" refers to a design check with benefit towards optimisation of the structure.

3 Design Review Systems

3.1 General

As mentioned, most societies have legally implemented appropriate strategies (reliability management systems (RMS)). These strategies differ in many aspects but commonly use design checking/review as powerful tool against errors. In structural design, this leads to the definition of two major engineering roles: the design engineer (whose work will be checked) and the design review engineer (who will perform the design check) (see [8] and [9]).

The roles of the structural design engineer (DE) and the design review engineer (DR) are described in detail in the RMS. RMS represent the level of building control during design and execution of a project. Thus, RMS can be interpreted as the defense strategy against human error. However, as it is the last line of defense it is imperative that human error should already be tackled before the design documents leave the design office and buildings go into execution.

RMS differ fundamentally from society to society. The respective state administrates the responsibility by granting building permits. Consequently, the RMS is linked to the building permit. Every nation has different legislation so that the RMS exhibit minor or major differences. However, the RMS can be divided into two general types (see [3]).

3.2 Repressive System

A typical version of a repressive system is explained by the example of the system applied in France. For issuing a building permit, the responsible building authorities only check zoning aspects and the building master plan. Structural integrity is within the responsibility of the parties involved with the construction: architect, contractor and owner, who are legally obligated to design and build up to the relevant codes. However, fulfilment is not to be checked by the authorities. The parties are also legally obligated to take out insurance policies to cover risks associated with the construction.

The advantage of this system is the financial safety in case of failure and damages since the insurance will cover possible claims. However, disadvantages are substantial – as reliability management based on this concept, does not focus on prevention of structural failure. It will only cover failure-induced costs and the costs for the structural design increases significantly due to the cost of the insurance policies. Design reviewing and site inspections are only performed if an involved party specifically requires these, e.g. the insurance might grant better policy conditions for the owner if design review is performed.

Concerning a repressive RMS it must be stated that unforeseeably high actions or insufficient structural strength as well as human error are not necessarily covered, since there is not a legal requirement to review the design before the building permit is granted. A building permit may be obtained without design and execution supervision. Therefore, it is absolutely reasonable to argue whether this approach can be categorised as a RMS as reliability is not tackled in technical terms. Only the possible consequences are looked after.

However, design and execution supervision often happens in the respective societies under private law as a requirement by the insurer of the project.

3.3 Preventative System

Contrary to the repressive system, the preventative or preemptive system aims to avoid structural failure in general by consequent design supervision and review before the permit is granted, and on-site inspections for checking of the execution. In contrast to the repressive system, by definition, this approach is a real RMS. A typical example for a preventative system is the system applied in Germany, presented in Figure 1. In this system, a full design review by a highly qualified and chartered design review engineer has to be performed and reported to the building authorities before the building permit is granted. During construction, the design review engineer is responsible for checking all the relevant design drawings as well as for performing sample inspections of the execution (e.g. reinforcement in situ). The disadvantages of this system lie within the possibly larger inertia in the design and execution phase as an additional, economically independent party is involved. However, this additional party introduces advantages into the design and execution process as it provides the prevention of failures and cost-efficiency because additional insurance policies are not required.

Compared to the identified causes for structural failure, the following must be stated: Unforeseeably high actions or insufficient structural strength as well as human error are covered since there is a legal requirement to check the design before the building permit is granted, e.g. in Germany the detailed report of the design check is a requirement for granting a permit. A building permit cannot be obtained without design and execution supervision. After completion, the design review engineer has to provide another, finalising report.

The advantages of the preventative system, however, can only be utilised if the independence of the DR is guaranteed. True independence can only be achieved under the pre-requisite of economic independence. Considering that the client will pay for both the services of the DE and DR, economic independence can only be achieved by a mandatory, legally required assignment. In the German system, this is the case for most structures. As the fee for the DR is part of a strict pay grid and also collected by a building authority, it can be considered an addition to the accessory costs related to construction (such as taxes, permitting fees etc.).

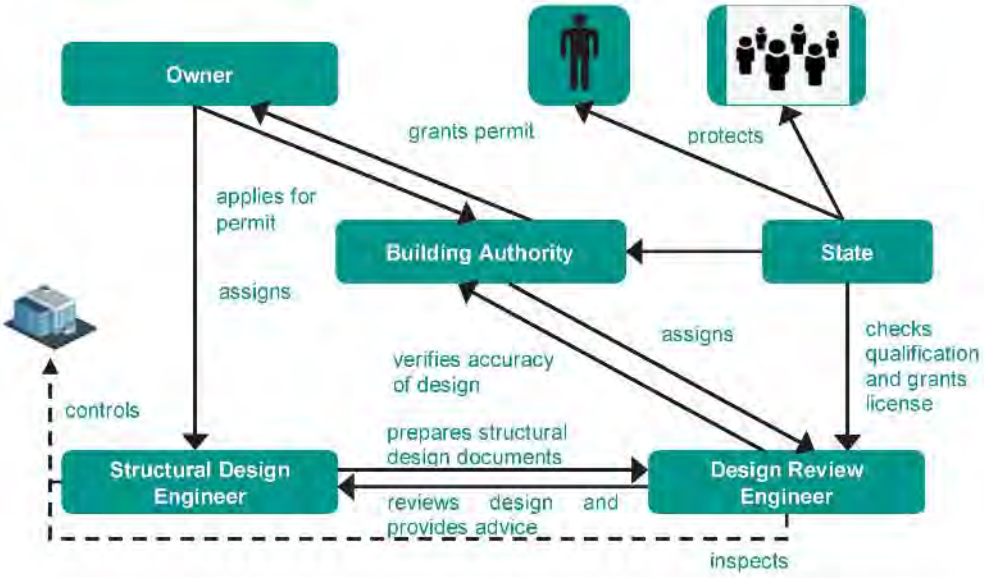

Figure 1. Preventative system by the example of the German system [3]

4 The Different Roles of the Engineer

In every RMS, two roles apply to the engineers: the design engineer, who develops a design solution, and the design review engineer, who reviews and checks the design (for detailed information see [8] and [9]). As the client is the originator of the risk to the society, he has to pay for both of them, though the design review engineer may be assigned directly from a governing body or the building authority. Since structural failure is very rare, many clients consider the design review engineer a necessary evil, especially if the design review engineer interprets his role more as a pure design checker (due to matters of simplicity, only the male form will be used in the following). The actual relationship of DE and DR may be one of three types:

(1) The DR interprets and conveys his role as a form of construction police. The DE accepts this role and is afraid of the identification of errors.
(2) The DE is not afraid of error identification but relies on the DR to find such. This may lead to a sloppier approach to the structural design.
(3) The DE and the DR interpret their roles as part of a team to generate a better and optimised structural solution. In this version, it is important to maintain a professional distance to avoid harming the independence of the design review.

The client's acceptance of the design review depends on the felt outcome. If the DR follows the first type, the DR may be perceived as a cause of problem by delaying actual construction.

The second type, however, may lead to a low identification rate of human error, since the DE is tempted to reduce his own self-check efforts. From the authors' experience as consulting engineers, however, this is rarely the case because the design engineer understands the liability issue (the liability mostly remains with the design engineer, not the design review engineer) and a flawed design will harm the firm's reputation. Additionally, the design review engineer does not solve possible mistakes for the DE, he will require additional documentation and verification. This again leads to more effort. Thus, relying on "design aid" by the DR will only cause inefficient design and disadvantages for the design engineer.

The third type is surely the preferred one, providing the client with the experienced highly qualified and independent review of another expert. The possible issue arises with the DR possibly getting too involved into the design process so that an independent and distant review may be unlikelier. But, when the parties involved act in a highly professional manner, it is not very likely that there is a collusion concerning this matter.

It is always beneficial if any problems found during the process that might be useful to other designers are publicised through a reporting mechanism such as CROSS [11].

The following examples, taken from the authors' day-to-day practice, give an insight of the benefits of a "collaborative" design review. Special emphasis will be laid on the advantages gained for the client.

5 Examples of Successful Design Review

5.1 General

The following examples provide anonymous information from real projects.

5.2 Geotechnical Structure

The first example deals with the design of the geotechnical structures needed for foundations of a sequence of two bridges comprising of an extradosed structure with a maximum span of 100 m and a multi-span composite structure with a span of up to 31 m shown in Figure 2 as they are to be built on challenging soil conditions. Underneath a layer of relatively dense gravel with a thickness of about 5 m, soft clay with a depth of 150 m – 300 m is in place. Considering the magnitude of the bearing forces of the bridge structures – 50 MN and larger – a shallow foundation within the gravel was not considered. Also, a pile foundation, initially proposed by the designers, reaching down to the bedrock was not an option. Hence, a combination of a raft and a pile foundation with pile lengths between 35 m and 50 m was developed in collaboration between the involved parties during the design review process.

The idea behind this concept is the enhancement of the weak soil by reinforcing it with piles of moderate length and creating a sufficiently stiff, embedded "foundation block" comprising of the raft foundation, the piles and the soil between the piles. To achieve this, it was necessary to interlock the soil and the piles by suitable means, i.e. by additionally driven displacement piles (see Figure 3).

Figure 2. Extradosed and multi-span composite bridges ©OVB

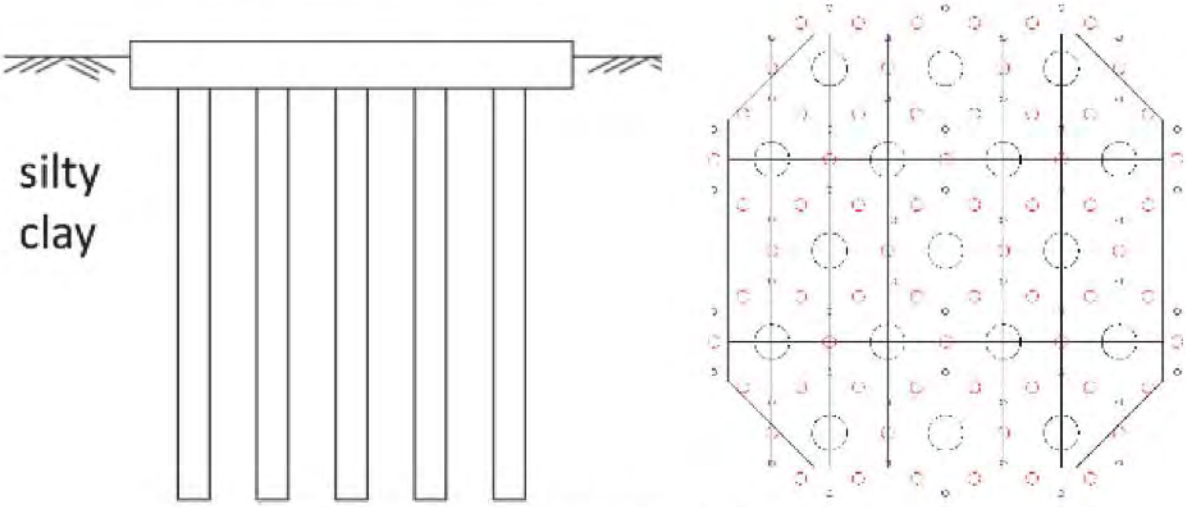

Figure 3. Combination of raft and pile foundation

To derive the relevant mechanical properties of the pile-soil-interaction and to describe the load distribution between the pile assembly and the raft foundation extensive in-situ survey and theoretical study was necessary. Implementing the mechanical characteristics gained into the structural model of the foundation and using complex non-linear material laws for describing the soil leads to the lump-sum elasticity-constants – non-linear vertical and horizontal stiffness k_v and k_h – used for analysis of the superstructure of the bridges.

The design review required a technically independent plausibility check of these results calculated by finite-element-methods, as the load-deflection-behaviour of the bridge foundations and the resulting soil-structure-interaction define critical design states for the superstructure of the bridges as well as for the foundations. This task was facilitated by the fact that the stiffness difference between the silty soil and the raft-pile-foundation is of such a proportion that raft, piles and the soil in the immediate vicinity act as a stiff, compact element. By suitably adapting the fundamental Boussinesq-half-space-solution [10] it is possible to establish the above mentioned lump-sum elasticity-constants using an alternative path.

5.3 Conversion of an Existing Bridge

The problem underlying the second example arose from the task of converting an existing road-bridge with a steel superstructure and a lightweight orthotropic deck slab into a steel-concrete composite structure. This became necessary, as the steel components of the deck slab suffer significant fatigue-induced damages as consequences of an increased amount of HGV-traffic (Figure 4) and the complete replacement of the bridge was not an option due to restraints resulting from operating boundary conditions.

Figure 4. *Fatigue induced cracks in the deck slab*

One major consequence of this conversion is the significant increase of dead load due to the weight of the new concrete deck, which results in substantial geometrical challenges concerning the gradient of the driving surface. For this reason, the designer proposed a temporary shoring of the steel superstructure to induce a deflection in the opposite direction prior to pouring the concrete. As this action is sensitive in many aspects – i.e. creep and shrinkage of the concrete, stiffness distribution between steel superstructure and concrete amendment, foundation problems for the shoring etc. –, the design review process led to a solution without propping the steel superstructure by using mono-strands as permanent external prestressing of the bridge (Figure 5).

The advantages of this solution are obvious:

- No need of temporary foundations
- Suitable prestressing prior to concreting
- Additional load-bearing-capacity for the bridge's superstructure
- Possibility of re-tensioning to accommodate time-depending deformation components
- Economically advantageous solution

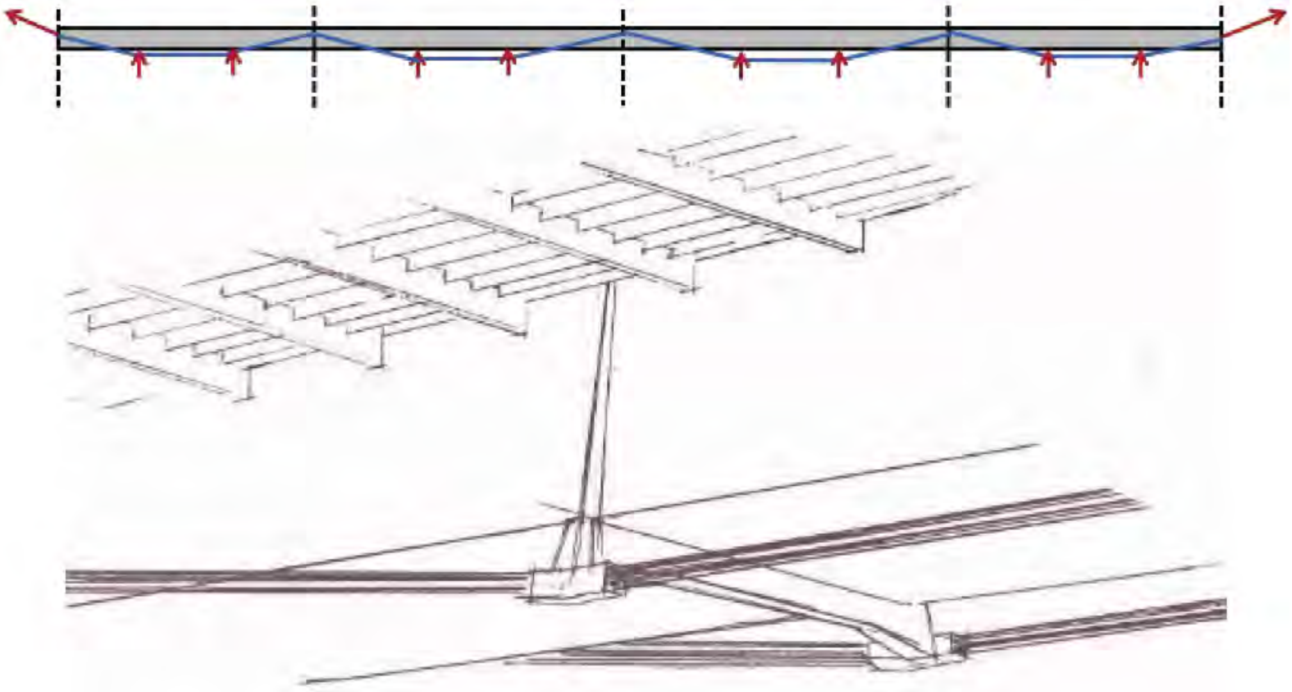

Figure 5. *External prestressing to avoid temporary shoring ©Baumann+Obholzer*

5.4 Bottom of an Excavaction Pit

Recently a technical design review for a multi-storey excavation pit for a high-rise building with four basement floors was conducted. Concerns were raised by the design review engineer regarding the overall design. The design review engineer acted as coordinator of interface between the designer of the construction pit and the structural design engineer. Thus, before even starting the detailed review of the structural design and the key drawings, a couple of simple questions were posed due to plausibility checks in the draft design of the construction pit. These questions concerned

- the thickness of the foundation slab,
- the average storey height of the basement floors,
- the thickness of the slabs depending on the live load,
- the existence of an interception slab, e.g. above the first basement floor,
- the requirement for additional space for the HVAC and further installations.

By these simple questions an fundamental design improvement was triggered which, in the end, led to lower the bottom of the excavation pit about 1.20 m further. A revised version of the structural design was handed in for review before the actual review work had even started. The revised version of the design was reviewed before the assignment and became part of the tender documents between the client and the contractor.

Due to a independent and free review approach providing an external view of the overall design, substantial improvements for the client and the design engineer were achieved. This example shows the advantages of conducting a design review even at earliest stages in the design process and by using the design review potential for assessing the interfaces between the involved parties. Figure 6 illustrates the design models of the original geotechnical and the improved structural design.

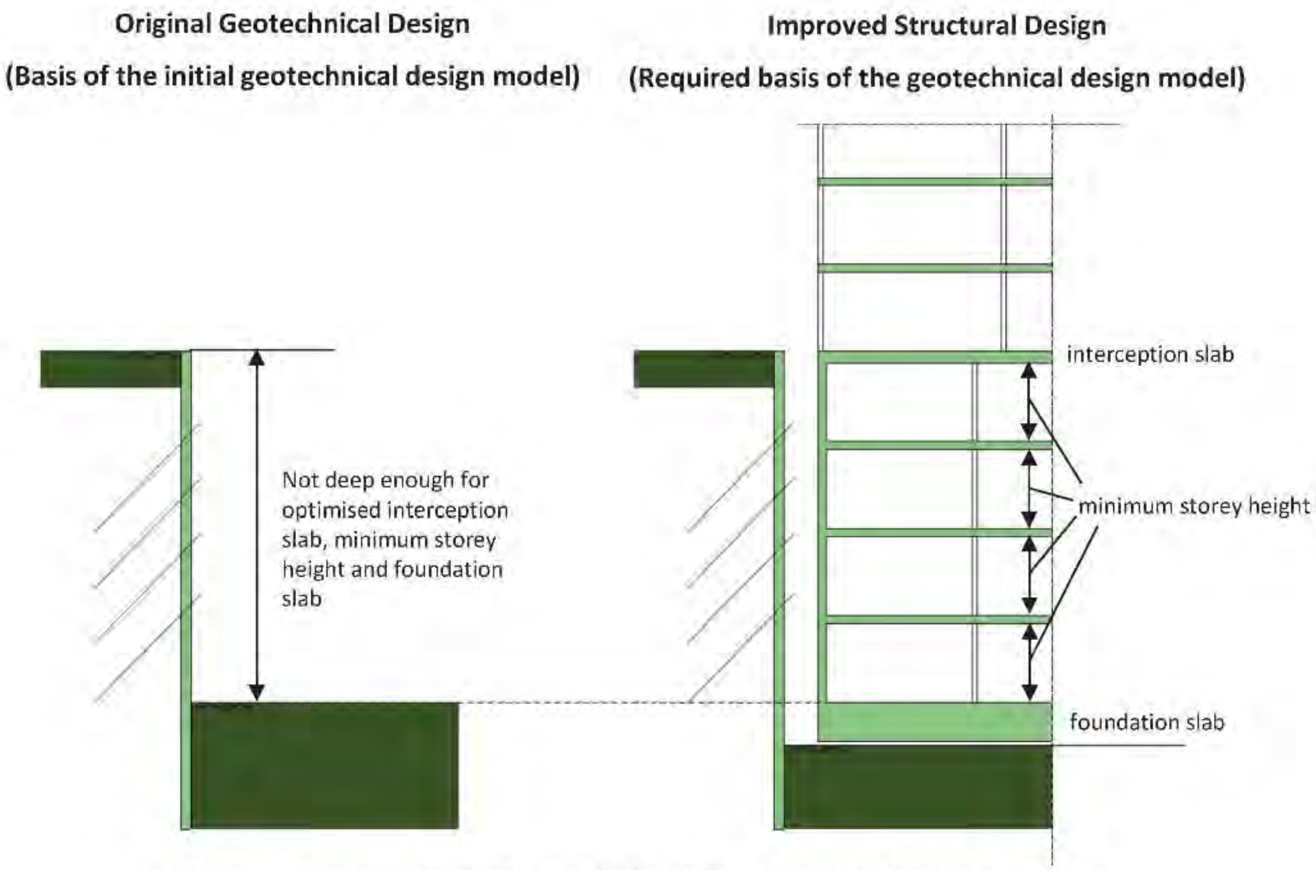

Figure 6. *Design models before and after initial review of the construction pit*

6 Database for Improvement of Design Review

The examples provided in section 5 showed the importance of design review in terms of coordination of interfaces between the involved parties to derive an optimized design solution. To improve the efficiency of the design review and to avoid the repetition of similar design issues, databases of possible design flaws and improvement potential have proven useful. Such databases do not function as tools for denunciation but provide valuable information for future structural designs. A prominent one is CROSS [11], which is based on confidential reporting of design issues and provides the corresponding reports to the public. However, these databases can only grow and improve if reports of design issues find their way in to them. Thus, it is essential that design engineers as well as design review engineers provide their valuable experiences to them.

7 Conclusion

This paper provided a general oversight of possible methods of design review and the corresponding roles of the design engineer and the design review engineer. Practical examples show and proved that a mutual or collaborative approach, the understanding both roles as a team joining forces to achieve a better structure, is to be pursued and beneficial for the involved parties. It is also found, that successful design review requires the design check to be independent in every way - economically, personally and technologically.

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Praktische Beispiele für eine erfolgreiche bautechnische Prüfung

Der vorliegende Artikel liefert einen allgemeinen Überblick über mögliche Methoden der bautechnischen Prüfung und die entsprechenden Rollen des Tragwerkplaners sowie des Prüfingenieurs innerhalb eines Zuverlässigkeitsmanagementsystems (RMS). Anhand von praktischen Beispielen wird gezeigt und bewiesen, dass ein kollegialer Ansatz, bei dem sich beide Rollen als ein Team verstehen, für die beteiligten Parteien vorteilhaft ist. Hierbei ist es wichtig, dass die bautechnische Prüfung in jeder Hinsicht wirtschaftlich, persönlich und technologisch unabhängig erfolgt. Des Weiteren differenziert der vorliegende Beitrag zwischen einer „Bemessungsüberprüfung", sprich: der Überprüfung des Tragwerkplaners durch einen Experten, und einer „Bemessungsüberarbeitung", also der Bemessungsüberprüfung mit dem Nutzen zur Optimierung des Tragwerks.

In den meisten Gesellschaften existieren inzwischen Zuverlässigkeitsmanagementsysteme als Verteidigungsstrategie gegen menschliches Versagen. Hierbei ist ein präventives System (wie z.B. in Deutschland) einem repressiven System, welches die Zuverlässigkeit aus technischer Sicht nicht gewährleistet, vorzuziehen. Eine reine Rollenunterscheidung zwischen Tragwerksplaner und Prüfingenieur ist jedoch nicht ausreichend, da es auch auf die Beziehung zwischen den beiden Rollen ankommt. Es können folgende Rollenverständnisse gefunden werden:

1. Der Prüfingenieur sieht sich als eine Art „Baupolizei" und macht sich lediglich die Fehleridentifizierung zur Aufgabe, was oftmals vom Tragwerksplaner aus Angst akzeptiert wird. Hierdurch kann es passieren, dass der Prüfingenieur als Problemursache angesehen wird, durch die es zu Bauverzögerungen aufgrund der Planungsträgheit kommt.

2, Der Tragwerksplaner hat keine Angst vor der Fehlererkennung und verlässt sich sogar auf den Prüfingenieur, wodurch ein sorgloseres Vorgehen bei der Bemessung praktiziert werden kann. Dies führt zu einem Anwendungsfehler des RMS, da der Tragwerksplaner die Selbstkontrolle vernachlässigt, und somit zu einer niedrigen Identifizierungsrate von menschlichen Fehlern. Zudem kann eine Bemessungshilfe durch den Prüfingenieur zu unwirtschaftlichen Konstruktionen und Nachteilen für den Tragwerksplaner führen.

3. Der Prüfingenieur und der Tragwerksplaner agieren als Teil eines Teams, um eine bessere und optimierte Bemessungslösung zu erzielen. Diesbezüglich ist es wichtig, eine professionelle Distanz zu wahren, um die Unabhängigkeit der bautechnischen Prüfung nicht zu gefährden. Wird dies beachtet, so wäre der 3. Fall das Optimum.

Zuletzt werden Datenbanken zur Verbesserung der bautechnischen Prüfung behandelt. Derartige Datenbanken enthalten Beispiele aus einer positiven Koordination der Schnittstellen, um eine optimierte Entwurfslösung abzuleiten. Diese Datenbanken können nur wachsen und verbessert werden, wenn Berichte über Designfragen hiermit verknüpft werden. Daher ist es von wesentlicher Bedeutung, dass der Tragwerksplaner und der Prüfingenieur ihre wertvollen Erfahrungen zur Verfügung stellen, um als Informationsquelle für zukünftige Konstruktionen zu dienen.

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Design Review as a Powerful Tool to Address Human Factors: A Collaborative Approach

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DOI: 10.1080/10168664.2020.1754145

Abstract

Human error is the major cause of structural collapse. Design review, together with execution control, is the most effective way to remove human errors from the building process and therefore most societies have procedures for design review and execution control installed. These systems work differently, e.g. preventive or repressive, and consequently affect the involved parties differently. In this paper, the effect of different design review and execution control systems on the acting engineer as an individual will be assessed by addressing human factors that influence design decisions. The paper will focus on the structural design engineer and the benefits of a well-tuned collaboration between the design engineer and the design review engineer, who also performs on-site inspections. The goal is to provide a better understanding of the impact of the design review and execution control procedure on the individual as well as on the development of the project. Human factors affect the design engineer subconsciously and influence the decision making in a significant way. Awareness of these factors and the corresponding influence due to the design review and execution control system will improve the design outcome and the relationship between the design engineer and design review engineer.

Keywords: human factors; design checking; supervision; failure causes; prevention

Introduction

The protection of human life and its physical integrity, and the protection and conservation of nature, are fundamental human rights and consequently a crucial part of a nation's legal framework. In terms of structural engineering, this leads inevitably into an area of tension between structural safety and efficiency. Hence, to provide the level of safety accepted by society without making structures inefficient and unaffordable, different approaches for design review and on-site building control have been developed and chosen by various countries.[1]

In design, sufficient structural integrity is widely thought to be achieved through the application of partial safety factors which are deemed to define the necessary distance between the design values of the actions and the design value of the resistances. These safety factors are derived from prediction models and stochastic assessment, i.e. the design problem is formulated under uncertainty to account for variations in so-called (random) basic variables, such as the magnitude of the actions, material strengths, geometric deviations and uncertainty in the prediction models. From there, the reliability of a structural component can be determined by the use of advanced algorithms (see Refs. [1] and [2] for further information). Note that reliability is a characteristic property of a member that can be compared to the target reliability, which is given in design codes (e.g. in Europe, EN 1990[3]).

To make this design strategy feasible for day-to-day application, the results of these reliability analyses define the basis of deduction of deterministic approaches to account for the reliability of structural members with the widely used (semi-probabilistic) partial safety factor concept. In other words, partial safety factors account for uncertainty related to extreme actions and material properties as well as geometric properties falling below the reference levels, i.e. uncertainties which can be described by mathematical methods using a set of preset conditions to cover extreme deviations from the mean sufficiently. This explains why the number of structural failures due to extreme actions in combination with significant deficits in structural strengths is fairly low (see the section "Human Errors", below).

Human errors, however, are likely to lead to entirely new conditions as these cannot be covered by the probabilistic techniques used in structural design. Thus, the academic structural system "without errors" requires a totally different verification from the real-world structural system "subjected to errors", i.e. by their very nature, the partial safety factors commonly applied in design do not account for human errors.

In a conventional engineering assessment, the physical cause of structural failure is addressed by referring to the verification schemes and the underlying structural safety concept of the design codes. As human error is the major cause of structural collapses,[4] it is, however, more crucial to be aware of possible fields of these errors and the required mechanisms and methods to avoid them (see "Causes of Failure", below). These mechanisms and methods have to be known and understood to develop strategies for tackling the problem of human errors successfully. Consequently, this leads to the development of an advanced reliability management system (RMS) to cover both parts of the problem.

The acceptance of such an RMS by all involved stakeholders, i.e. the building authority, client, designer, contractor, etc., depends largely on the benefits gained. As the discussion of this issue may span from comments such as "RMS make construction works more complicated and hence more expensive" to "RMS are crucial for the overall success of the project", it will be shown in the following, starting with an analysis of the causes of failure, that the implementation of a preventive RMS will deliver the benefits needed for acceptance within both the society and the structural engineering community by introducing a "collaborative" design review carried out by an independent—technically as well as economically—design review engineer. These benefits will become obvious when comparing the outcome of the upstream or preventive review with the results of a downstream RMS, the latter being focused on dealing with the consequences of design deficits, in most cases by settling financial claims against the design engineer, instead of preventing them.

Causes of Failure

Structural failures have been documented since the recording of events. In ancient times, structural failures were considered to be acts of God, since the events happened unexpectedly and were often disastrous. Nowadays, a well-based insight into the fundamental structural behaviour, and hence a scientific assessment of the structure to be investigated, is facilitated by the use of sophisticated methods and tools for the structural analysis. However, structural failures still occur. Research into the structural failures shows that the causes can primarily be categorised as:

A. Failures due to unforeseeably high actions or insufficient (aleatory) structural strength, or a combination of both.
B. Failures due to human error.

Cause A refers to structures with appropriate design according to the valid design codes and standards at the time of design and construction. Failure then occurred owing to extremely high loads which exceeded the characteristic values of the actions according to the appropriate codes in conjunction with insufficient material strength. Failure due to this cause is unlikely and is normally covered by safety concepts, i.e. a sufficiently small overlap between the factorised design values of the actions and the design values of the corresponding resistances (such as partial safety factors), as mentioned in the Introduction. *Figure 1* shows a schematic representation of this principle. Here, E denotes load effects, R denotes resistances, γ_i represent partial safety factors, and p_f is the overall failure probability. It should be noted that an error in the code, which is subject to very intensive review, does not constitute a human error in this paper.

Cause B is responsible for failure in almost every case, as structural failure commonly includes human error in at least at one stage of the design and construction process. *Table 1* shows the typical causes of structural failures in a more detailed listing. This table is based on the findings of Ref. [5]. In the corresponding analysis, only 6% of failures were found to be caused by unforeseeable events. By far the larger portion of failures is caused by human errors that, ideally, might have been prevented by the application of an appropriate system for design review and execution control.

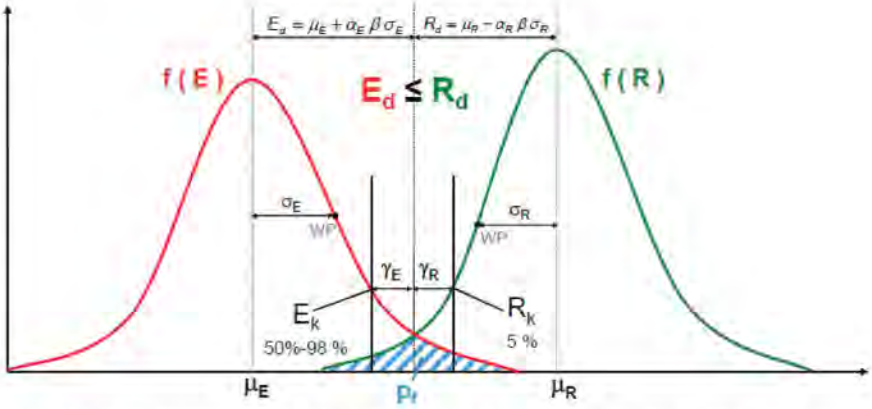


Fig. 1: Schematic representation of the semi-probabilistic safety concept using partial safety factors

Cause of failure	% of total damages
Ignorance, carelessness	37
Insufficient knowledge	27
Underestimation of influences	14
Forgetfulness and mistakes	10
Unjustified reliance on others	6
Objectively unknown situations and influences	6

Table 1: Causes and distribution of structural failures according to Ref. [5]

Human Errors

Error Classification

Human error can be classified into three basic categories: mistakes, slips and lapses.[6,7] Errors can be differentiated depending on the sequence and execution of the relevant process.[8] A mistake is a correct execution in an incorrect sequence of actions, a slip is defined as incorrect execution of a correct sequence of actions, while a lapse is defined as omitted or left-out actions.

In addition, human errors can be defined as manifest and latent.[8] While manifest errors are committed by people with direct contact with the structure, such as construction workers, latent errors are committed by others, such as designers. The latter cannot check the consequences of their work immediately, as a design error may only be found once the structure is under execution. Manifest errors will reveal themselves as errors immediately.

Human errors can also be categorised according to the information processing in the human mind and the subsequent actions.[9] A distinction can be drawn between three modes: knowledge-based, rule-based and skill-based.

- Knowledge-based errors occur despite the utmost diligence as a result of incomplete or inaccurate understanding of the designed system and its materials, and is often fostered by overconfidence and people's tendency to prefer information that confirms their preconceptions.
- The rule-based mode refers to errors that occur as a result of the blind application of rules, e.g. using a wrong rule or the right rule incorrectly. The psychological reason for these types of errors is the faster achievement of the design results

and the lower effort on a conscious level.
- The skill-based mode refers mostly to slips that happen as a result of strong routines in solving design tasks (e.g. typographical errors).

Causes of Errors

Human error can occur at every stage in the life circle of a project, i.e. during development, realisation and use, not only during design. Therefore, it has to be taken into account and avoided during design and execution as well as during service. According to Ref. [4], human error is divided almost evenly between design and construction phases. In additionally, the often referred to "calculation flaw" has proven to be only a minor reason for serious design errors. Failure does not necessarily happen within the first years in the service life of a structure, even though it is more likely.

To be able to identify possible human errors, one needs to be aware that human errors of the types explained in *Table 1* do not happen without a reason. Commonly mentioned reasons[11] are:

- time pressure and too low engineering fees
- pressure to minimise the costs of the structure to be built
- insufficient coordination of the design
- black-box-type use of design software
- lack of detailing
- large number of new standards and design rules.

Assessing these issues, it becomes clear that human error, and consequently structural failure, is caused to a large extent by systemic and cultural features.

The two main causes (A and B; see "Causes of Failure", above) of structural failure must be tackled efficiently. While cause A (failure due to unforeseeably high actions or insufficient structural strength) can be counteracted by corresponding design concepts stated in the relevant design codes, cause B (human error) requires an organisational set of measures, referred to as a quality management system (QMS) or reliability management system (RMS). Possible strategies for implementing the QMS or RMS may be provided in codes. In the European standardisation efforts, this is stated in EN 1990,[3] Annex B, although it is arguable whether a design code is appropriate for dealing with this issue, bearing in mind that the RMS has to address considerably more aspects than just the structural design. The set of measures presented, for instance in Annex B, includes design supervision and site inspections, which have proven to be effective methods to identify and prevent human errors.[10]

The actual reasons for human errors are manifold and can be found at all stages/phases of the project. Restricting the deliberations to the design phase, error may occur at the personal level of the design individual or at the management level of the organisation. Having this in mind, the authors suggest, by condensing the common categorisation, the following three categories only: executive management, personal, and imposed externally and culturally.

- **Executive management.** This category refers to all errors that could have been prevented by proper management within the organisation, such as errors related to staff rotation, overestimation of technical skills of the project team, poor coordination of tasks or lack of quality control. In addition, work overload of the design engineers due to poor management in the assignment of tasks should be considered in this category. Lack of motivation or boredom of the design staff should also be assessed since a reasonable pay grid, as much as the right positioning of the design tasks, is the responsibility of the management. Another important factor within the management's responsibility is communication. The management has to make sure that communication within the project teams is successful. Communication with other parties involved in the project requires excellent project management to make sure that individuals as well as information technology-based tools can communicate successfully.
- **Personal.** This category refers to the causes of errors within the individual, i.e. mainly psychological and sociological reasons, such as personal stress due to interpersonal conflicts or excessive personal ambitions. Other reasons in this category may reflect personality flaws such as ignorance, indolence or greed. Certain human traits will contribute as well, such as intentional withholding of information to avoid consequences or attempts at solving the issues without further (and required) assistance. The latter, in particular, is often a result of a highly stressed job market and the misconception of admitting the need for assistance as being a sign of weakness or underperformance. Another important aspect is the advanced development of design software in combination with changes in the education of engineers. There is a strong tendency, especially among recent graduates, to trust in engineering software without the necessary intellectual distance. The reasons for this are a generally deeper relationship with software and technology among young people ("digital natives"), and a shift in education away from the "hard" subjects (such as mathematics or structural mechanics) to software application. The organisation can improve this tendency by providing an environment for open discussion and change, especially between junior and senior staff.
- **Imposed externally and culturally.** This category refers to all causes that are imposed on the organisation from a political or societal level, such as new, more complex design codes, financial pressure due to flawed budgeting, or high workload due to low interest rates and consequently the appreciation of "concrete gold", for example. However, it is the management's responsibility to provide the best possible framework for the project in reaction to the imposed influences. As an example, imagine that the structural design for a large public project is assigned to an engineering company. The company has to fulfil the design task within a certain time frame, so that enough staff has to be on the job, often requiring the hiring of further staff. Now, it is not unusual that politically exploited public budgets have to be stretched over several years (contrary to the original schedule), leading to a significant delay in the project. This will require the design company to take on further projects to provide enough work for all staff. At some, often unknown, point in time, the work on the large public project has to resume,

> usually without much notice, but then under increased time pressure. In this case, the management has only limited options to react, especially considering the strict legal framework concerning employment rights.

Further externally imposed sources of human error include the growing extent and complexity of the set of rules and regulations to be followed. Beside the considerable legal national and international framework, in Europe, this is mostly caused by the process of European integration and harmonisation. The elaboration and development of the Eurocodes led to standards that multiplied the number of pages several times compared to the previous relevant national code generation (e.g. the DIN code series in Germany).

From these thoughts, the large responsibility in the avoidance of human error of the individual, the executive management of the design organisation and the governing body becomes clear. While the social issues, leading to errors, need to be dealt with on the political floor by adjusting the sociolegal framework, the fulfilment of due diligence and the correct application of an RMS need to be delivered by engineers.

RMSs to Counteract Human Error

General

To counteract human errors, most societies have implemented corresponding strategies in their legal framework. These strategies differ in many respects (see the following two subsections), but commonly use design review as a powerful tool against errors. In structural design, this leads to the definition of two major engineering roles: the design engineer (whose work will be reviewed) and the design review engineer (who will perform the design review).

The roles of the design engineer and the design review engineer are defined within the RMS. As the RMS represents the building control during the design and execution of a project, an RMS can be seen as a line of defence against human error. However, it is the last line of defence; ideally, human error will already have been tackled before the design documents leave the design office and buildings go into execution.

RMSs differ internationally owing to the peculiarities of the respective societies. In general, the nation's executive body administrates this responsibility by granting building permits. The RMS is consequently linked to the building permit. As every society has different legislation, the corresponding RMSs exhibit minor or major differences. However, in principle, an RMS can be classified regarding the underlying philosophy into two general types: the downstream method and the upstream or preventive method. The downstream method relies on the awareness of the collective responsibility of all involved parties and becomes active if structural deficits or failures happen. In contrast, the upstream method is active from the very beginning of the project by using the well-known and proven concept of the "independent second opinion" to identify critical situations and hence to establish an environment of prevention of structural deficits or failures by exchanging and challenging different design approaches and opinions.

As explained, addressing the human factor goes far beyond mathematical correctness. Tackling the psychological aspects is crucial for this task. Hence, it is noteworthy that in the upstream discussion of design solutions, the challenge of standing up against a second opinion will be more effective in avoiding misjudgements than the downstream or mending strategy. Furthermore, by using the upstream method, additional benefits for the structural design may be gained through the contribution of the independent opinion of a second expert.

Repressive RMS

A typical version of a downstream RMS is explained through the example of the procedures used in France. For the issuing of a building permit, the building authorities only check zoning aspects and the building master plan. Structural integrity is the responsibility of the parties involved in the construction: the architect, contractor and owner, who are legally obligated to build to the relevant codes. However, fulfilment is not checked by the authorities. The parties are also legally obligated to take out insurance policies to cover risks associated with the construction.

The advantage of this system is financial safety in case of failure and damages, since the insurance will cover possible claims. However, the disadvantages are substantial: reliability management does not prevent failure in the first place and the structural cost increases significantly because of the cost of the insurance policies. Design reviews and site inspections are only performed if an involved party specifically requires these, e.g. the insurance may grant better policy conditions for the owner if a design review is performed. Compared to the causes of structural failure identified above, the following must be stated:

Cause A (unforeseeably high actions or insufficient structural strength) and cause B (human error) are not necessarily addressed since there is no legal requirement to review the design before the building permit is granted. A building permit can be obtained without design and execution supervision. However, design and execution supervision often happen under private law.

Preventative RMS

In contrast to the downstream RMS, the upstream or preventative system attempts to avoid structural failure in general by consequent design supervision, before the permit is granted and by on-site inspections to check the execution. As already laid out, the basic idea of this RMS is the elimination of design and execution deficits and the prevention of small- or large-scale structural failures by challenging the proposed design solution with a second, independent opinion.

A typical example of a preventive RMS is the system applied in Germany and explained in *Fig. 2*. In this system, an independent design review has to be performed by a highly qualified and chartered design review engineer and the essential results of the review have to be reported to the building authorities before the building permit is granted. During construction, the design review engineer is responsible for checking all the relevant execution drawings as well as for performing sample inspections of the execution (e.g. in situ reinforcement control).

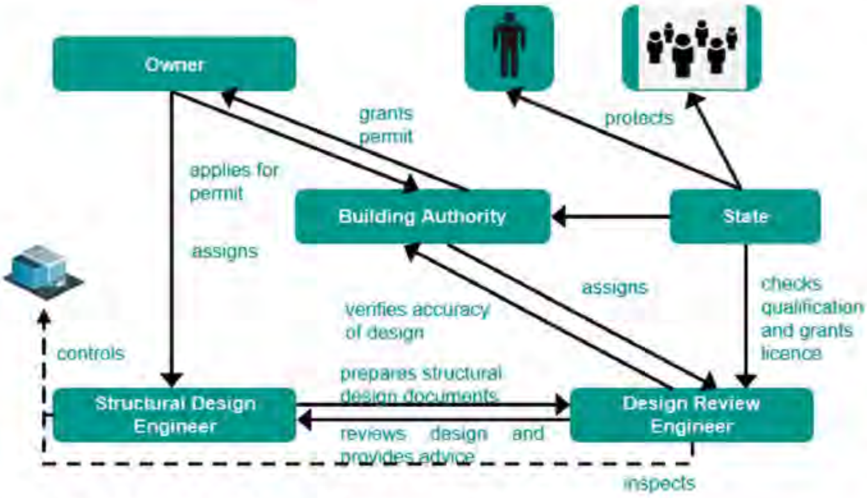


Fig. 2: Preventive/upstream system: the German system

Possible disadvantages of this system include the risk of generating extra inertia in the design and execution phase, as an additional, economically independent party is involved. But with this player, it is also possible that significant benefits for the design and execution will be achieved for the project, as the input of the design review engineer provides a qualified second opinion to prevent failures and to increase cost efficiency, since additional insurance policies are not required and improvements to the design are possible.

Compared to the identified causes for structural failure, the following must be stated:

Causes A and B are covered since there is a legal requirement to check the design before the building permit is granted, e.g. in Germany the detailed report of the design review is a requirement for granting a permit. A building permit cannot be obtained without design and execution supervision. After completion, the design review engineer has to provide another report.

The preventive RMS is sometimes criticised for the possible reliance of the design engineer on the design review engineer, leading to a flawed design in the hope that the design review engineer will find any mistakes. From the authors' experience with medium-sized and large projects, however, this is generally not the case because the design engineer understands the liability issue (in general, the liability lies with the design engineer, not the design review engineer) and a flawed design will harm the firm's reputation. In addition, the design review engineer does not solve possible mistakes for the design engineer, but will require additional documentation and verification. This again leads to more effort. Thus, relying on "design aid" by the design review engineer will only cause inefficient design and disadvantages for the design engineer.

Role of the Design Engineer in an RMS

In the upstream system, the design engineer is also the engineer responsible for the outcome of the project. If structural failures occur and errors in the design are identified, the design engineer, who actually performed the design, will be held responsible: not the owner of the design company, and not necessarily the person who signed off on the design. If the damage is only economic, the design company's insurance will step in, with most likely severe consequences for the engineer who performed the design in terms of career opportunities. This puts the engineer under permanent pressure and leads to ongoing self-checks during the work process.

The design engineer is responsible not only for structural integrity but also for all aspects of serviceability. Whereas the design review engineer, in his or her role as representative of the building authority, may only address issues regarding structural integrity, the design engineer will be held responsible for every issue related to the structure. Since damage and failures in terms of serviceability (cracks, deformations, etc.) are far more likely to occur than structural failures, the pressure on the design engineer is significant.

As the design engineer is part of the design organisation, the causes of human error should be efficiently addressed within the organisation.

Role of the Design Review Engineer in an RMS

Assessing the role of the design engineer and the fundamental condition of a technically and economically independent review, it is logical that the design review engineer is not the responsible engineer for the outcome of the project in an upstream system. The design review engineer, however, is responsible for safeguarding the structural safety. Structural failure despite a design review having been performed can directly lead to the loss of the design review engineer's licence, which is not only a massive economic loss but also a loss in reputation. Owing to the small number of chartered design review engineers (in Germany, there are approximately 650, across all possible fields of expertise: concrete and masonry structures, steel and composite structures, timber structures and fire protection), the workload is significant. Thus, not every design review can be performed by the design review engineer personally, even though the design review engineer will sign off on the design review report and will be informed about the project and the corresponding issues. Nonetheless, the design review engineer puts a large amount of trust in his or her staff since errors may lead to direct personal consequences, as the review licence is assigned to a person, not to a company or an organisation.

Limitations of RMSs

The upstream RMS described in the subsection "Preventive RMS" provides a framework for counteracting human error based on the principle of a second opinion and an independent review of the structural design. However, it does not provide detailed guidance on how to avoid human error regarding the human factors mentioned in the section "Human Errors", earlier in the article.

These errors are undeniably orchestrated by human factors which are fostered by various mechanisms. While the common RMSs focus on identifying and finding human errors in the design documents and during execution, thus not preventing human errors but detecting and fixing them, the prevention of human errors in terms of reduction of the likelihood of their occurrence should be a major part of enhancing an RMS.

Suggested Methods of Counteracting Human Error

General

It is sometimes mentioned[9] that the consequences of human error can be incorporated into the design procedures by, for example, assuming the appropriate value of probability of failure. This seems impossible since human error changes the entire limit state and consequently cannot be grasped by mathematical methods alone. Imagine a column under compression. The engineer may have estimated the buckling length incorrectly owing to a misjudgement of the support situation. The failure mode of the column may then change from compression failure on a cross-sectional level to buckling. No safety factor, no matter the quantity, will solve this issue and provide a safe and efficient solution. Thus, human error must be covered by purposeful measures defined within the RMS.

Based on the findings of the previous section, the RMS should be extended to reduce the probability of human errors instead of focusing only on their identification. In the following subsections, ways of enhancing the avoidance rate of human errors will be explained.

RMSs Inside the Organisation

As developed in the subsection "Causes of Error", the management of a design organisation plays a major part in avoiding human errors. Besides the approaches to limiting pressure on the individual design engineer, the design organisation should provide a framework for sufficient training and education to make sure that the chosen design and the procedures for verifying it are state of the art. Although ongoing training is a requirement for members of the engineering associations, it is not a legal requirement for every design engineer. Thus, the management of the design organisation needs to set a mandatory requirement to pursue further training and must provide a sufficient amount of time for this. As simple as this sounds, smaller design organisations, in particular, will face severe issues in substituting the loss of personnel during training sessions.

Error Management System

Another opportunity for design organisations is to adopt an open way of dealing with errors by assessing and publishing them internally, e.g. through intranet sources or internal workshops. Every error is also an opportunity for growth and lessons learned, and should be treated accordingly.

Some engineering communities have established routines for the anonymous publication of design errors, such as CROSS (Confidential Reporting on Structural Safety) in the UK.[11] This allows for a steady improvement of the RMS strategies and for a generally better understanding of human error in structural design tasks.

Cultural Change

However, the major aspect of avoiding human error by the design engineer should be an effective way of tackling the causes of human error mentioned in the subsection "Causes of Error", which are mostly related to the pressure to which the design engineer is subjected. In a fast-moving industry with large budgets at stake, pressure cannot be avoided completely; however, it can be limited and taken off the individual's shoulders. The major aspect here should be a cultural change: away from a price-driven market to a quality-driven one; away from passing down the responsibilities from top to bottom, towards strong leadership that protects the lower levels of the hierarchy. While smaller design organisations with a flat hierarchy, often consisting of the owner and a handful of engineers, have been shown to fulfil this goal, larger organisations tend to have a wider spread of responsibility. Pressure thus can only be reduced if large as well as small design organisations can work in a supportive environment in terms of fair compensation and market share.

To shift the system-immanent competition from price to quality, some countries have introduced fee grids for engineering services. The public sector is legally required to keep to these grids, whereas the private sector can still negotiate freely. Investigations by several engineering associations in Germany, as well as the authors' practical experience, show that the private sector will almost always try to avoid the pay grids and hence undermine the basic intention of these grids to replace the price competition with a quality competition. This can be extremely frustrating for the design organisations, especially keeping in mind that it is not typical in other lines of work that have pay grids (e.g. physicians and lawyers).

To be able to work efficiently, design organisations are forced to take on larger workloads, which will put too much pressure on the individual. A difference can only be made through society-wide changes in the thinking of leaders, similar to a code of ethics, to quote according to the pay grids and enable the provision of good compensation for the design engineer, thus reducing pressure and stress and increasing the societal value of the occupation. Within this context, a good design review by a technically and economically independent expert can only improve the situation for the client, the design organisation and the individual design engineer. This, however, will only be true if the design review happens on a collegial level, seeing eye to eye, i.e. the design review engineer must understand his or her position not as a checker or teacher of the design engineer but as a catalyst to improve the design for the benefit of all participating parties.

Collaborative Review

To illustrate how good collaboration between the design engineer and design review engineer, and good handling of the human factors involved, will lead to improved design results, an example of the authors' practices is presented. This example will show how benefits can be achieved for every party involved in the project. The role of the RMS in setting the conditions for such a successful outcome will be analysed as well.

The problem underlying this example arose from the task of converting an existing road bridge with a steel superstructure and a lightweight orthotropic

Fig. 3: Fatigue-induced cracks in the deck slab

deck slab into a steel–concrete composite structure. This had become necessary as the steel components of the deck slab had suffered significant fatigue-induced damage as a consequence of an increased amount of heavy goods vehicular traffic (*Fig. 3*), and the complete replacement of the bridge was not an option owing to restraints resulting from operating boundary conditions.

One major consequence of this conversion was the significant increase in the dead load due to the weight of the new concrete deck, which resulted in substantial geometric challenges concerning the gradient of the driving surface. For this reason, the designer proposed a temporary shoring of the steel superstructure to induce a deflection in the opposite direction before pouring the concrete. As this action would be sensitive in many aspects, e.g. creep and shrinkage of the concrete, stiffness distribution between the steel superstructure and concrete amendment, and foundation problems for the shoring, the design review process led to a solution without propping up the steel superstructure using mono-strands as permanent external prestressing of the bridge (*Fig. 4*).

The advantages of this solution are obvious:

- no need for temporary foundations
- suitable prestressing before concreting
- additional load-bearing capacity for the bridge's superstructure
- possibility of readjusting the tensioning to accommodate time-dependent deformation components
- an economically advantageous solution.

These advantages could only be realised through the a successful handling of the human factors involved. This means that the applied preventive RMS with a chartered design review engineer provided an independent view on the design engineer's solution. The design review engineer was already involved at the early design stages, so that an understanding of the actual challenges in the project could be achieved. This differed significantly from the common approach in which the design review engineer is solely responsible for the checking of the design solution derived by the design engineer, and thus led to a deeper understanding of the design engineer's situation and thus to a more collegial collaboration. Consequently, different design approaches could be discussed openly and freely without the parties holding back ideas. Thus, the early involvement of the independent design review engineer led to a more relaxed and less error-prone environment. The fact that the design review engineer had a powerful say in the whole project hierarchy owing to the public assignment gave the design engineer the required freedom to derive the best solution in a dialogue with the design review engineer. This good collaboration provided the design engineer with a feeling of back-up and deeper understanding by an important party in the design process.

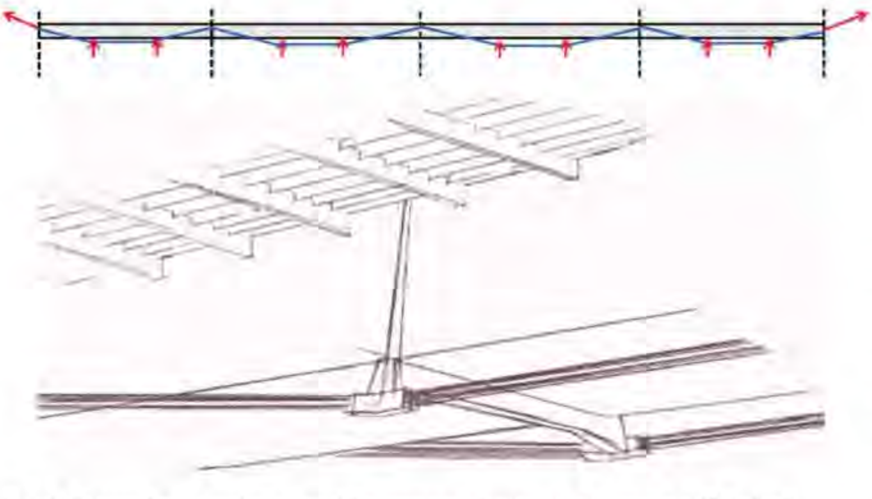
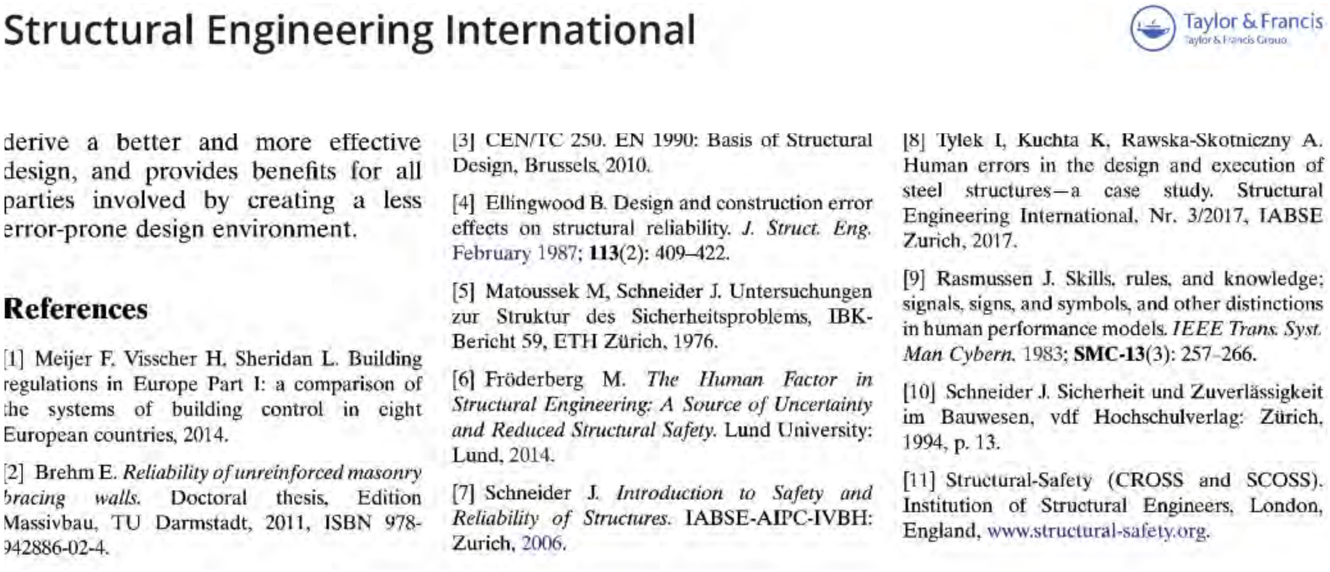


Fig. 4: External prestressing to avoid temporary shoring (© Baumann + Obholzer)

In terms of the definitions of the human factors in the section "Human Errors", the personal factors, in particular, could be addressed effectively and in a cooperative manner. The chosen procedure follows the stipulation of cultural change presented in the subsection "Cultural Change".

Conclusions

It is intuitive that human error is the main reason for structural deficits, damage and failure. Most societies impose an RMS to avoid human error due to design flaws and mistakes. However, further causes of human error, rooted in personal aspects of the individual and management of the design organisation, are not covered by the commonly used RMSs. This paper points out that this more effective strategy to prevent human error requires the individual and, especially, the management to act accordingly. Suggestions for improvements are presented, such as error management systems and transparent pay grids. Furthermore, a cultural change within the engineering community and society is discussed and derived as the main factor in avoiding human error. In an example, good collaboration between the design engineer and design review engineer based on the well-known principle of a second, independent opinion is shown. Good collaboration uses the potential of a technically and economically independent expert to



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derive a better and more effective design, and provides benefits for all parties involved by creating a less error-prone design environment.

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Die bautechnische Prüfung als mächtiges Werkzeug, um menschliche Faktoren zu berücksichtigen: ein kooperativer Ansatz

Die Ursache für das Tragwerksversagen ist in den allermeisten Fällen auf menschliche Fehlhandlungen zurückzuführen. Menschliche Fehlhandlungen können in statischen Berechnungen nicht berücksichtigt werden. Menschliche Fehlhandlungen werden begünstigt durch eine Vielzahl von Faktoren, wie z.B. Zeitdruck, mangelnde Planungskoordination usw.. Diese wiederum hängen u.a. vom Einfluss der Geschäftsführung, individuellen Problemen des Personals oder politischen und sozialen Aspekte ab.

Darüber hinaus werden Fehler differenziert in offensichtliche Fehler (während der Bauausführung) und verborgene Fehler (während der Planung). Zudem kann eine Kategorisierung in drei Fehlermodi erfolgen. So existieren wissensbasierte, regelbasierte und fähigkeitsbasierte Fehler.

Der vorliegende Artikel liefert die Klassifizierung der menschlichen Fehlhandlungen und einen allgemeinen Überblick über mögliche Methoden, diese in der bautechnischen Prüfung zu vermeiden. Die entsprechenden Rollen des Tragwerkplaners sowie des Prüfingenieurs innerhalb eines Zuverlässigkeitsmanagementsystems (RMS) werden dahingehend beleuchtet.. Anhand eines praktischen Beispiels wird veranschaulicht, dass ein kooperativer Ansatz zwischen dem Tragwerksplaner und dem Prüfingenieur viele Vorteile bringen kann. Nur wenn beide Parteien auf Augenhöhe, aber dennoch unvoreingenommen, an der Optimierung des Tragwerksentwurfs arbeiten, kann ein Mehrwert generiert werden.

In den meisten Gesellschaften existieren inzwischen Zuverlässigkeitsmanagementsysteme als Verteidigungsstrategie gegen menschliche Fehlhandlungen, die an die Baugenehmigung und somit den Staat gebunden sind. Hierbei ist ein präventives System (wie z.B. in Deutschland) einem repressiven System, welches die Zuverlässigkeit aus technischer Sicht nicht gewährleisten kann, vorzuziehen.

Die größte Einschränkung von Zuverlässigkeitsmanagementsystemen besteht aktuell darin, dass sich diese oftmals auf die Identifizierung von menschlichen Fehlhandlungen beschränken, anstatt diese im Voraus zu verhindern. So könnten menschliche Fehlhandlungen zum Beispiel durch regelmäßige Schulungen reduziert werden. Des Weiteren sollten sogenannte Fehler-Management-Systeme eine anonyme, aber dennoch offene Kommunikation von Fehlern ermöglichen. Hierdurch können vergangene Fehler als potenzielle Lernquelle dienen, um gleichartige Fehler zukünftig zu vermeiden. Auch ein kultureller Wandel weg vom preisgesteuerten hin zum qualitätsorientierten Markt könnte das Entstehen von menschlichen Fehlhandlungen minimieren.

IMPRINT / IMPRESSUM

PUBLISHED BY / HERAUSGEBER
German Federal Association of Design Review Engineers for Structural Integrity
and Fire Protection
Bundesvereinigung der Prüfingenieure für Bautechnik (BVPI)
Dr.-Ing. Hartmut Kalleja, Kurfürstenstraße 129, 10785 Berlin

PRINTED BY / DRUCK
Vogel Druck und Medienservice, Leibnizstraße 5, 97204 Höchberg

DTP
Satz-Studio Heimerl, Scherenbergstraße 12, 97082 Würzburg

Print Run / Auflage: 5500