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HUMAN FACTORS IN STRUCTURAL ENGINEERING

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SUMMARY

Core Elements of Human Factors taken from the Aviation Sector are examined in the context and relevance to Structural Engineering.
Design tasking research carried out in Sweden is reviewed together with other research findings on error management.
Greater understanding and consideration of Human Factors can lead to improved outcomes in Structural Engineering.
Attitude and Values and the role of Empathy are considered.

INTRODUCTION

“Has anyone here ever made a mistake?”

Captain Niall Downey a pilot with Aer Lingus asked attendees at the beginning of a conference on Human Factors organised by the Royal College of Physicians and Surgeons of Glasgow (Peakin 2019) asked the same question. A delegate answered, ‘Every day’ Captain Downey responded, “so we are in the right room In aviation we assume that we are going to make mistakes and our whole mindset and system is based around that’.

If a flight crew make a mistake chances are everyone dies with them.

If a Structural Engineer makes a mistake they can usually walk away from the experience and in many cases that mistake is not discovered until an extreme environmental even such as a major earthquake occurs.

Almost 50% of Structural Failures are the result of human error (Fruwald et al 2007).

Losses from errors in Structural Engineering are significant and have been assessed as adding 4% to the costs in Sweden, 7% in an Australian study and 4% in a Dutch study (de Haan 2012).

Self-Checking of designs results in over 2.4 times the chance of errors compared to independent checking (de Haan 2012).

Results from 17 independent Swedish Engineers who were set two design tasks on two projects varied over a range of 300%. (Frodeberg 2019).

BACKGROUND

Significant structural engineering mistakes continue to be in the headlines in NZ media. Something is going wrong! These join a long list of others that show that repeated mistakes by different engineers continue to be made.

Charting the number of deaths and incidents in aviation from 1920, showed a steady climb to 1977, then a descent to a point now where there are fewer than 1000 deaths a year in commercial jet aviation worldwide out of around 4 billion passenger movements.
In 1977 two Boeing 747 passenger aircraft collided on the runway at Tenerife airport, killing 583 people.
That was a watershed moment in aviation said Captain Downey," We decided as an industry, that we needed to do things differently. It began as "cockpit resource management'" and became 'crew resource management', and has evolved over the past 40 years into full-blown" Human Factors."
The study of Human Factors has helped and continues to help make significant improvements in Aviation Safety.

Other industries have taken on Human Factors especially those in safety critical or high-risk areas including transportation, oil & gas, process and nuclear. The Medical profession in the UK recently called on Aviation experts in Human Factors to improve the performance in hospitals.

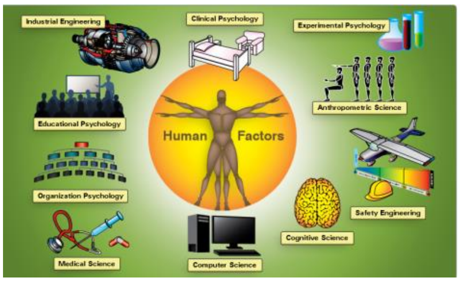
The published information on Human Factors in Structural Engineering focusses mainly on errors and failures but little on other aspects.

Structural Engineers study materials and structural systems but little about the people that are performing structural engineering.

STRUCTURAL ENGINEERING

'The art of using materials that have properties which can only be estimated.
To build real structures that can only approximately analysed
To withstand forces that are not accurately known'
SO THAT OUR RESONSIBILTY WITH RESPECT TO PUBLIC SAFETY IS SATISFIED

HUMAN FACTORS



"Figure 1" Human factor disciplines

The term 'human factors' refers to the wide range of issues affecting how people perform tasks in their work and non-work environments. The study of human factors involves applying knowledge about the human body and mind to better understand human capabilities and

limitations. Human factors are the social and personal skills which complement technical skills. Understanding and applying human factors is crucial for safety because of the continued threat of failures and accidents.
The 9 core headings are taken from NZ CAA documents. There are different ways of describing Human Factors not all of which have negative connotations.

Threats and Errors
Organisational Factors
Stress and fatigue
Information acquisition and processing
Situational awareness and workload management
Decision making
Communication
Leadership and team behaviour
Automation, vigilance and monitoring

The following introductory descriptions summarise some of the most important factors under each of the headings.

THREATS AND ERROR

Threats are generally defined in aviation as events or errors that compromise safety.
Errors can be slips and lapses (skill-based errors), carrying out an action incorrectly, and mistakes where the action is incorrect. These types of human error can happen to even the most experienced and well-trained person and were covered in more detail at the initial Engineering NZ Webinar of the series “Lessons Learned (2020)”. Threats and errors are part of everyday aviation operations that must be managed by the aviation professionals, since both threats and errors carry the potential to generate undesired states. Structural Engineering errors are important and are the subject of most of the published studies (de Haan 2012 and Froderberg 2019).

ORGANISATIONAL FACTORS

The culture of an organisation is critical in aviation where a ‘Just Culture’ (No blame reporting of incidents and mistakes) is encouraged. SOP development and checklists based on human factors are made. A lack of appropriate resources can interfere with one’s ability to complete a task. It may also be the case that the resources available, including support, are of a low quality or inadequate for the task. When the proper resources are available, and to hand, there is a greater chance that we will complete a task more effectively, correctly and efficiently.
A happy workplace where openness, good communication and positive support encourages higher productivity and fewer errors and mistakes.

STRESS AND FATIGUE

Fatigue is the general term used to describe physical and/or mental weariness which extends beyond normal tiredness. Physical fatigue often leads to mental fatigue. Mental fatigue, which may include sleepiness, concerns a general decrease of attention and ability to perform complex, or even quite simple tasks with customary efficiency.

Stress; There are many types of stress. Chronic stress is accumulated and results from long-term demands placed on the physiology by life’s demands, such as family relations, finances, illness, bereavement, divorce, or even winning the lottery. When we suffer stress from these persistent and long-term life events, it can mean our threshold of reaction to demands and pressure at work can be lowered. Thus, at work, we may overreact inappropriately, too often and too easily.

Stress and fatigue affect structural engineers and should be monitored and mitigated as they can lead to errors and mistakes.

INFORMATION ACQUISITION AND PROCESSING

Information acquisition and processing involves attention and perception. Techniques for improving and enhancing memory and development of skills are especially important for both aviation and structural engineering training.

SITUATIONAL AWARENESS AND WORKLOAD MANAGEMENT

The process of attention, perception, and judgement should result in awareness of the current situation. Situation awareness has traditionally been used in the context of the flight deck to describe the pilot's awareness of what is going on around him, (i.e., where he is geographically, his orientation in space, what mode the aircraft is in, etc.). Situational Awareness is knowing what is going on around us and being able to predict what will happen next. If a person is unable to perceive, comprehend, or project what will happen with a hazard, then we could say they had a lack of situational awareness.

Workload Management is a process of distributing work among employees and monitoring people's utilization over time. The goal is to make sure the work is delivered within the planned time frame, but also to keep a healthy balance in terms of the amount of work every team member needs to do.
Workload management is important because there is a unique relationship between job demands, intellectual demands and job satisfaction of an individual. With workload management, space is created in the team's schedules to allow the best work to be delivered. Giving the team a realistic plan with prioritized tasks and attainable deadlines can help achieve the goal of delivering projects on time and on budget and is applicable in both aviation and structural engineering.

DECISION MAKING

Attention and perception shortcomings can clearly affect decision making. Perceiving something incorrectly may mean that an incorrect decision is made, resulting in an inappropriate action. We depend on memory to make decisions. Sensory and short-term memory have limitations, both in terms of capacity and duration. It is also important to bear in mind that human memory is fallible, so that information may not be stored or may be stored incorrectly.
These factors are relevant for both aviation and structural engineering.

COMMUNICATION

Poor communication often appears at the top of contributing and causal factors in aviation accident reports, and is therefore one of the most critical human factor elements. Communication refers to the transmitter and the receiver, as well as the method of transmission. Transmitted instructions may be unclear or inaccessible. The receiver may make assumptions about the meaning of these instructions, and the transmitter may assume that the message has been received and understood. With verbal communication it is common that only 30% of a message is received and understood. Good communication is critical in structural engineering to ensure effective design. Poor communication is a common feature encountered in engineering disciplinary cases.‘

LEADERSHIP AND TEAM BEHAVIOUR

Leadership is difficult to define but is obvious when seen. In essence it is the ability to harness diverse personalities to achieve an objective.
All of the human factors are required to develop individuals into a team in order to achieve outcomes that are greater than the sum of the parts. This applies to both aviation and structural engineering where most tasks and operations are team affairs.
Cultural differences may mean that team members are unable to express concerns and or to not allowing other to express their concerns and this creates ineffective communications and damages teamwork. Unassertive team members can be forced to go with a majority decision, even when they believe it is wrong and dangerous to do so.

AUTOMATION, VIGILANCE AND MONITORING

Automation plays a vital and increasingly dominant role in aviation. Vigilance is closely related to situational awareness. Workplace procedures, such as scanning, two-way communication and use of checklists will help to maintain vigilance. Effective monitoring is important in aviation with special techniques to ensure effective active monitoring. The increasing and more extensive use of automation in structural engineering requires similar vigilance and monitoring. Understanding of assumptions that the automation is based on together with vigilance and monitoring of outputs is critical in structural engineering as more of the traditional design activities are taken over by automation.

Some other human factors from the aviation sector have relevance to structural engineering.

DIRTY DOZEN (Dupont 1993)

The 12 most common causes of error accident precursors within aviation maintenance:
Lack of communication, Distraction, Lack of Resources, Stress, Complacency, Lack of teamwork, Pressure, Lack of awareness, Lack of Knowledge, Lack of Teamwork, Lack of Assertiveness, Norms. Many of these have been already covered and some others are obvious. **Distraction** is a real threat to structural engineering especially with devices and social media. **Pressure** is to be expected when working in a dynamic environment when the pressure to meet a deadline interferes with the ability to complete tasks correctly, then
it has become too much. However, one of the most common sources of pressure is our selves. We put pressure on ourselves by taking on more work than we can handle, especially other people's problems, by trying to save face and by positively promoting superpowers that we do not possess. Learning **assertiveness** skills will allow a worker to say 'No', 'Stop!', and communicate concern with colleagues, clients, and the organisation. These skills are essential, and when deadlines are critical, then extra resources and help should always be obtained to ensure the task is completed to the required level of quality. Workplace practices develop over time, through experience and often under the influence of a specific workplace culture. These practices can be both good and bad, safe and unsafe; they are referred to as "the way we do things round here" and become Norms. Unfortunately, such practices follow unwritten rules or behaviors, which deviate from the required rules, procedures and instructions. These **Norms** can then be enforced through peer pressure and force of habit. It is important to Understand that most Norms have not been designed to meet all circumstances, and therefore are not adequately tested against potential threats.

SOME OTHER HUMAN FACTORS THAT MAY INFLUENCE STRUCTURAL ENGINEERING

Do different personality types affect the practice of structural engineering?
Are outcomes different for' high-risk takers compared to 'play it safe' personalities in structural design?
In aviation there is a saying "There are bold pilots and old pilots but there are no old bold pilots"

Do personality types play a part in some of the issues already described?
Is the engineer a ‘Team player’ or ‘Individualistic’ ?
What is the role of ambition, hubris and arrogance together with the more unsavoury aspects such as ’greed and avarice’?

The good short paper “Human Factors in Structural Failures” (Alvi 2015) contains a summary of the role of human factors in Structural Engineering Failures especially interesting is the example of the Quebec Bridge in 1907.

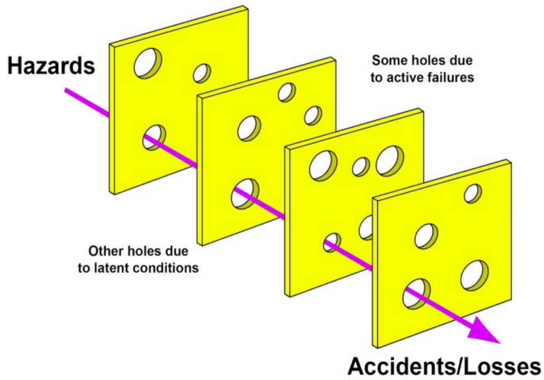
Work environment can affect human performance. Working in isolation and only considering one’s own responsibilities can lead to tunnel vision; a partial view, and a lack of awareness of the affect our actions can have on others and the wider task. Such lack of awareness may also result from other human factors, such as stress, fatigue, pressure and distraction.

It is important to build experience throughout our careers, especially concerning the roles and responsibilities of those we work with, and our own place in the wider Team. Developing foresight is essential in pre-empting the affects that actions may have on others. This is an attitude of professionalism and involves constant questioning *“what if …?”*

Asking others to check our work and challenge our decisions is useful in gaining the relevant experience and expanding our awareness.

THE SWISS CHEESE MODEL

A general model that characterizes the role of mistakes at several levels of an organization is the Reason model, alternatively called the Swiss cheese model.



“Figure 2“ The Swiss cheese” model of accident causation. (Reason et al., 2001)

Under the model, human mistakes are a managed risk. If a mistake occurs at a certain level within an organization, and it is not detected and eliminated at another level, this may lead to a critical situation.

ERROR SURVEYS ON STRUCTURAL FAILURES

The background and cause of structural failures has been systematically discussed and investigated in numerous error surveys, especially in the 1970’s and 1980’s it indicates that approximately 43% of the total number of failures are related to planning and design of the structure, 35% are related to construction, 15% are related to use or maintenance and 7% are related to other causes. The list is based on the results of different surveys, there is no consistent definition and clear division between the categories. Yet, it displays how a major portion of the total amount of errors may be related to the design phase.

COSTS OF DESIGN ERRORS

Human errors in design also have a large impact on costs in construction projects. According to a survey on 139 construction projects in Australia performed by Lopez and Love (2011) the design error costs were estimated to be as much as 7% of the contract value, regardless of procurement method and project type. Oter Dutch and Swedish studies indicate a lower rate of 3-4%. Based on GDP estimates for the construction sector and data from the PWC study of $15-20B Errors & Mistakes are costing in the order of $0.6-1.4B a year
Studies by Josephson and Hammarlund (1999) based on defects from seven building projects, indicate that the primary causes for design defects are lack of knowledge (44%), information (18%) or motivation (35%).

UNCERTAINATIES IN STRUCTURAL ENGINEERING

The task of practitioners of structural engineering is to synthesise a solution which meets their client's requirements (Froderberg, 2019).
Not only must a structure be designed or assessed to be safe, but it must meet functional, performance and environmental requirements and be delivered at an acceptable cost. Uncertainties abound in the engineering and in all the activities associated with it. The engineer however must progress his task. Action is required based on predictions followed by decisions taken despite uncertainty. This is the essence of engineering. (Menzies, 1999). Uncertainty is a perpetual companion to all structural engineers.
Through design, we construct imaginary buildings with uncertain geometry; with materials of uncertain strength and quality; to withstand loads and environmental conditions of uncertain magnitude and kind. To this the human factor is added, which means that an uncertain amount of errors and deviations from what was intended, will be incorporated in the product. These uncertainties, and the variation of nature, are sometimes obscured to the practicing engineer as design codes and regulations have evolved to regulate and manage some of the most important uncertainties, e.g. loads and material parameters.

Commented [GH1]:

ENGINEERING MODELLLNG UNCERTAINTY (EMU)

This measure developed by Froderberg (2019) on how subjective decisions related to e.g.: experience; knowledge; conceptual understanding and design code interpretations, together with contingencies (things not yet certain) will induce variation and uncertainty in results from structural engineering calculations. Relatively well-defined engineering tasks generate a large variation when solved by different engineers. EMU has a large impact on structural safety. The EMU is time dependent and will typically decrease throughout the design process, as the contingencies will be reduced. This is relevant to understand and account for, especially for decisions made at an early stage, if those will be difficult or costly to change. The use of advanced tools and extensive modern "buggy" knowledge may have been developed as biased best practice among structural engineer's in design codes. These may, through their black-box resemblance and focus on detailed input, have a negative effect on the development of experience, knowledge and conceptual understanding.
Normally a correct solution is not obtainable. This means that a range of acceptable solutions is more appropriate than a single value. Values outside of this range may be considered errors.

Studies by de Haan (2012) indicate that Self-Checking of designs results in 2.4 -3 times the chance of errors compared to independent checking (de Haan 2012).

This is a significant finding and reinforces the critical role that effective quality assurance including the use of comprehensive and detailed checklists for all engineers and highlights the advantages of independent review.

SWEDISH ROUND ROBIN DESIGN INVESTIGATION

Seventeen engineers were paid to carry out two design tasks but given limited time to carry out the tasks (Froderberg, 2019)
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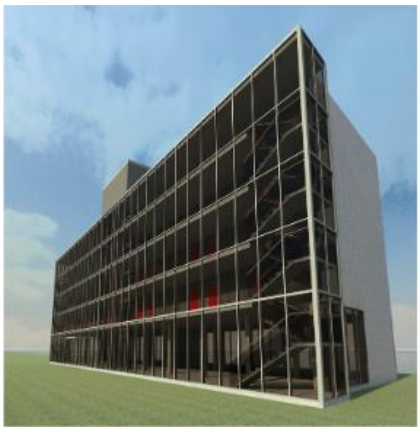
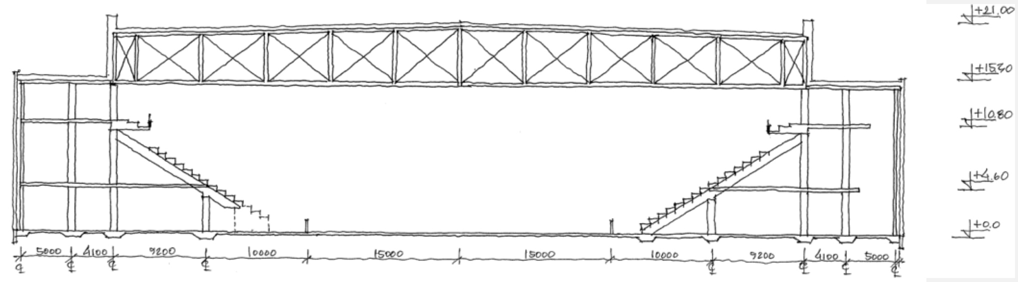
Test 1. A five-storey concrete building.



“Figure 3”

Test 2. A 68 m span truss for a stadium roof.



“Figure 4”

This investigation was divided into two separate tasks; both designed to resemble real design situations and performed individually by the participants. The first task was the preliminary design of a five-storey concrete building and the second was the conceptual design of a 68 m span roof structure. A qualitative interview was held afterwards.
The results from the investigation reveal a large variation between engineers.

The ratio between the lowest and highest value of the column design loads of the first task, is approximately three (for the majority of the individual columns). This variation is related to differences in total applied load but, more importantly, to the distribution of loads between columns.

Engineering Modelling Uncertainty *EMU* is used to describe the importance of subjective decisions performed in the transformation from architectural drawings to computational models, the term introduced. This uncertainty has a large impact on structural safety. The second task resulted in a geometrically uniform truss design. The estimated steel weight of the trusses varied between 20 and 50 tonnes.

An important finding from interviews of the participating engineers is that the majority of the engineers experienced a lack of review of calculations from their practice. This may explain why faulty knowledge has developed into biased best practice. The use of advanced tools and complex design codes prevents young engineers from the development of knowledge and conceptual understanding, as these tools force their users to focus on details rather than the whole problem; in particular if they are used with limited supervision to compensate for lack of knowledge.

WHAT MAKES A GOOD WORKPLACE AND A GOOD ENGINEER?

A happy workplace where openness, good communication, a 'Just' culture will provide greater satisfaction for all workers and create greater productivity and fewer mistakes.

The 'YouTube" video by Rod Machado "Defensive Flying" has some good points on Human Factors that are also relevant to structural engineering These include differences between Attitude and Values. Attitude is short term behaviour and can readily be manipulated change whereas values are long term developed over decades that includes what means most and is a backstop to decision making and making the right choice. Empathy can be the greatest advantage in understanding others but is also the greatest weakness especially if you do not want to disappoint. Understanding human nature, good self-reflection and a strong code of ethics and values help to make the right choices and to become a good engineer.

CONCLUSIONS

Better understanding of Human Factors and the development and implementation of systems based on these can improve the practice of structural engineering.
Positive aspects will flourish and measures to offset negative aspects will reduce errors, mistakes and failures.

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