Holistic steel structural design

Dr Kim Rasmussen explains how design-by-analysis will simplify and speed up steel frame structural design and deliver greater accuracy and safety

What led to your research into system reliability-based criteria for designing steel structures by advanced analysis?

The project came about firstly because of conversations with The University of Sydney's Architecture Faculty, from whom I learned that their design programs increasingly call on analysis programs that design structural components to find dimensions for things like floor slabs. The same programs would benefit from analysis programs that can design the complete structural frame so that the dimensions of columns and beams are known, thus allowing clear floor space and floor heights to be determined accurately during architectural design, avoiding a second iteration after structural design is completed.

Secondly, an Australian software producer, Strand7, released a product around the same time which featured 'advanced' analysis, and I started to receive enquiries from practising engineers about how to apply it.

Thirdly, advanced analyses of large structural systems can now be run on low-cost desktop computers, whereas 20 years ago, when the first advanced analysis programs were developed, they required high-cost high-performance computers and were only executed at research institutions.

Putting all this together, there were strong drivers to undertake research for a design-by-analysis tool for practising structural engineers.

Could you summarise your overall aims?

The aim is to make design-by-analysis the chosen method for designing steel structures. Current procedures rely on hundreds of equations stipulated in national codes for calculating the strength of individual components of structural frames, like columns and beams. These procedures will become obsolete when designing by analysis, as member strengths are implicitly checked. Most importantly, codes in design-by-analysis will stipulate the reduction factors (resistance factors in engineering design) to account for variabilities in key parameters like material strength, imperfections and loads. We aim to derive these factors for a wide range of steel frame applications.

What would you highlight as the most challenging aspects of your project?

Modelling geometric imperfections is tricky, particularly in 3D frames, and we've produced some nice work in overcoming this by making use of multiple elastic buckling modes and notional horizontal forces. It has also been challenging to map out a consistent framework for the probabilistic analysis of the system that considers variability in both the strength of the system and loads. We have done so for various combinations of dead, live and wind loads.

Our PhD students have been required to exercise great care in the planning and execution of Monte Carlo simulations. Each student may run about 100,000 advanced analyses of various frames. Administering, checking and processing such vast amounts of data has been one of their main challenges.

With whom are you collaborating in this project?

The team at Sydney includes Dr Hao Zhang, who is an expert in structural reliability, five PhD students, a Master's student and myself.

Additionally, we are collaborating with leading international researchers in the fields of steel structures and structural reliability.

Professor Bruce Ellingwood from the Georgia Institute of Technology, USA is one of the most eminent researchers in structural reliability and has contributed greatly to the project, particularly in setting out the overall framework for the reliability analyses for various types of load combinations.

Professor Benjamin Schafer from Johns Hopkins University, also in the USA, and I jointly supervised an MSc student from Johns Hopkins who worked on an aspect of the project related to tubular truss frames. Schafer is also likely to contribute to the part of the project related to the design of structures with slender cross-sections subject to failure by local and global buckling modes.

Professor Feng Fan from Harbin Institute of Technology, China, provides input related to the analysis and design of large-span space frames.

How do you foresee your research benefiting the Australian engineering profession?

The Australian structural engineering profession is agile in adapting to new technologies, which has helped it to stay competitive and successfully win bids for large jobs internationally. I believe the profession will adapt quickly to the methodology and that it will be implemented in Australian Standards without major resistance from stakeholders. Design-by-analysis will help Australian structural design firms to maintain their competitive edge. However, I don't see the benefits of this project being limited to Australia: over time, the design-by-analysis method will be adopted throughout the world.

A new paradigm for steel **frame design**

Research into the behaviour of steel structures at **The University of Sydney** is developing a computer-aided one-step methodology that will further innovation, while improving reliability and hence safety

IT IS EASY to take for granted the safety of the buildings in which we live and operate. In reality, of course, the dependability of built structures relies entirely on the skills and expertise of structural engineers. Steel frames act as the skeleton of many buildings, and are designed according to structural engineering principles and standards to ensure that their frameworks and supports will endure such events as high winds, earthquakes, fires and heavy snowfall, in addition to the pull of gravity and normal wear and tear. However, structures can collapse when not properly designed or built, particularly when encountering events they were not made to withstand.

Scaffolding structures are one area of construction in which a proportionally high frequency of collapse is encountered, and this is largely attributable to rogue practices on site. Here, the overall structural design may well be adequate, but if, for example, the scaffold is not anchored to the building as specified, certain members will fail and potentially cause a progressive collapse of the entire frame. When this occurs, workers' lives are at risk; however, until now, such incidences have garnered little attention because the public at large is generally not affected.

STRENGTH IN STEEL

Challis Professor Kim Rasmussen, Head of the School of Civil Engineering and Chairman of the Centre for Advanced Structural Engineering at The University of Sydney, Australia, finds the behaviour and design of steel structures fascinating because they can buckle despite apparent stability and may do so in different ways simultaneously: "Buckling comes in many modes which may interact and produce interesting and often beautiful patterns," he enthuses.

The strength and weight of the materials used are key to designing reliable steel frames, but the integrity of the structural components and the parts that connect them as a whole is paramount. The current method for steel frame design entails two stages: analysis of forces and moments in the steel frame, followed by detailed safety checks of columns, beams and connections against prevailing structural steel standards. Rasmussen is leading a project to develop a holistic method for ensuring reliability and therefore safety in a wide range of steel frame structures, while providing more flexible and efficient structural design processes. The method applies advanced geometric and material non-linear analysis, in which the current stages of analysis and capacity checking are carried out in a single step. At its core is rigorous computer-based statistical assessment of the whole frame strength, taking into account structural redundancy, failure propagation and statistical differences in loading and other variables: "Our method is superior to current member-based design to a national code: it is faster; provides more uniform reliability; and is versatile, being applicable to both common and unusual types of structural frameworks," asserts Rasmussen.

DEVELOPMENT METHODS

Rasmussen's team applied Monte Carlo probability modelling to obtain accurate figures for statistical distribution of frame strength. In this, all the variables were randomly assigned, such as width and thickness of steel sections, material yield stress and imperfections, including possible cross-correlations: "The problem is so complicated from a probabilistic viewpoint that it is the only way to accurately determine the distribution," notes Rasmussen. The simulations generated random structures with random values for such parameters as material strength, imperfections and residual stresses, where the statistics of the randomly-modelled parameters were consistent with field measurement statistics. The team then conducted advanced analyses of each frame to obtain and plot the frequency of strengths, and so determined the statistical distribution for a particular type of structure.

First-order reliability method analyses of various 2D frames have been carried out to obtain resistance

INTELLIGENCE

SYSTEM RELIABILITY-BASED CRITERIA FOR DESIGNING STEEL STRUCTURES BY ADVANCED ANALYSIS

OBJECTIVES

The project aims to change the paradigm of steel structural design, basing it on geometric and material advanced analysis in which analysis and capacity checks are carried out in a single step, thus obviating the need for member and connection capacity checks to a structural steel standard. The core of this project is a rigorous statistical assessment of the system strength which considers structural redundancy, consequences of failure and statistical variations in loading and variables affecting the frame strength. The main outcomes of this project are more consistent reliabilities of a wide range of structural systems, and shorter, more flexible and more efficient structural design processes.

KEY COLLABORATORS

Dr Hao Zhang, Senior Lecturer in the School of Civil Engineering, The University of Sydney, Australia

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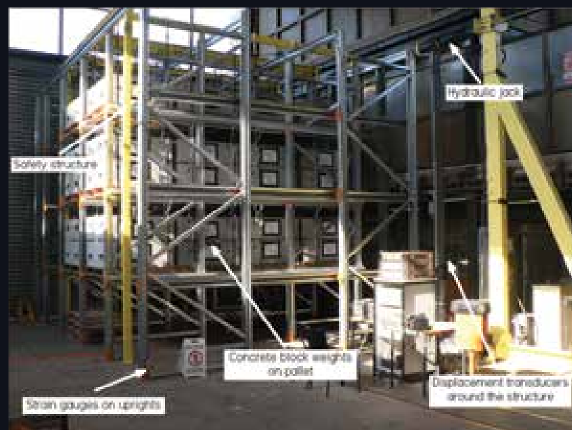
DR KIM RASMUSSEN is full Professor in the School of Civil Engineering at The University of Sydney. His research areas are theoretical and experimental structural mechanics with particular expertise in steel structural members and system, cold-formed steel structures, stainless steel structures, aluminium structures, and structural stability and analysis. He teaches advanced structural steel design to undergraduate and postgraduate students; serves on the editorial boards of the main international journals in the field of steel structures; and is Chairman of numerous Australian and international standards committees responsible for structural design standards for steel, stainless steel and aluminium structures.



Test frame in Structures Laboratory at The University of Sydney; steel frames in Brisbane (**left**) and Melbourne (**right**), Australia.

factors of specific layouts, under scenarios of varying load combinations and maximum acceptable probabilities of failure: the frames were designed to fail in many different ways, such as through beam or column yielding, column buckling and elastic sway buckling. From this work the team expected that resistance factors would depend on the particular failure mode. While this is the case, they have found that such dependency is relatively minor. The resistance factors also do not appear to be sensitive to whether or not a frame system is braced or unbraced, regular or irregular; or to what kind of load combination it is subjected. As a result, the set of resistance factors that Rasmussen and his team have gathered from a wide range of 2D structural frame types is remarkably consistent. From a structural design engineer's viewpoint, this as a positive result, minimising the number of resistance factors that will need to be incorporated. It is hoped that the same will apply once further analysis of 3D frames, space frames for roofs and frames with slender cross-sections have been completed.

In addition to using Monte Carlo methods, the researchers have devised methodologies for statistical modelling of random residual stresses and geometric imperfections in steel structural frames. One team member is analysing steel frames with cross-sections slender enough to distort under bending and compression in such applications as storage racks and industrial portal frames, determining appropriate models for geometric imperfections in local and distortional buckling modes, as well as models and associated statistics for stiffness of connections between columns and beams. New models of the behaviour of connections between I-shaped columns and beams in steel frameworks have also been developed. Though similar models have been proposed previously, these add value in the shape of a general framework that can be applied to 2D and 3D connections with multiple adjoining members.

FUTURE DESIGNS

The project will lay the foundations for the widespread use of computer-based design-by-analysis, integrating architecture and engineering, and fostering greater innovation in structural design. The team is optimistic that the Australian engineering industry will readily adopt the method, though is equally aware that it may not be as readily adopted in other countries where there is more conservatism and resistance to change among design engineers. Here, the group points to the precedent of a 20-year lag between adoption of design-by-advanced-analysis in the Australian standard for steel structures in 1990, and the incorporation of similar provisions in the equivalent American standard.

Rasmussen and his colleagues are working on modelling some of the main types of connections, though further work will have to be undertaken when the current project grant expires. Load combinations involving snow and earthquakes, which are not usually governing load combinations in Australia, will also be analysed. In the meantime, Rasmussen is encouraged by the positive feedback he has received so far from participants in the structural design arena: "I have been both commended on our work and encouraged to continue to develop the methodology with resistance factors for all types of frameworks and guidelines for creating associated nominal models," he comments.

Front: Francisco de Sena Cardoso, Dr Hao Zhang, Professor Bruce Ellingwood; **centre**: Adam Trouncer, Hannah Blum, Chen Zhu, Xi Zhang, Professor Kim Rasmussen; **back**: Wenyu Liu, Tanim Ahmed, Shabnam Shayan, Gengbo Chen.

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