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INTRODUCTION

This issue of “Current Steel Structures Research” for the *Engineering Journal* focuses on a selection of research projects at three European universities. The descriptions will not discuss all of the current projects at the schools. Instead, selected studies provide a representative picture of the research work and demonstrate the importance of the schools to the home countries—and indeed to the efforts of industry and the profession worldwide.

The universities and many of their researchers are very well known in the world of steel construction: the University of Sheffield in Sheffield, England; Luleå University of Technology in Luleå, Sweden; and the University of Trento in Trento, Italy. The studies presented here reflect elements of the projects as well as other significant ongoing activities. As has been typical of European engineering research projects for many years, most of the projects are multiyear efforts and many are multipartner efforts. This calls for very careful planning, cooperation and implementation of research needs and applications, including the education of graduate students and advanced researchers. As is also the case for American research work, the outcomes of the projects focus on industry needs and implementation of the results in design standards.

The lead researchers have been active for many years, as evidenced by their prominent roles in research and development in their respective countries, but they have also been frequent participants in projects elsewhere. Many English-language technical papers and conference presentations have been published, contributing to a collection of studies that continues to offer solutions to complex problems for designers, fabricators and erectors. Many of these projects complement past and current work from around the globe.

References are provided throughout this paper, whenever such are available in the public domain. However, much of the work is still in progress, and in some cases reports or other publications have not yet been prepared for public dissemination.

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SOME CURRENT RESEARCH WORK AT THE UNIVERSITY OF SHEFFIELD IN SHEFFIELD, ENGLAND

The University of Sheffield has been active in steel structures research for many years. For the past 20 years, the university has been a worldwide leader in the complex subject of the response of steel and composite structures to fire, with Professor Ian Burgess as the lead researcher. Research that began with the behavior of individual beams and columns is now focused on the performance of building structures as a whole. Attention to the subject was significantly expanded through the full-scale fire tests conducted on a composite frame at the Building Research Establishment at Cardington, England, during the 1990s, where the Sheffield group participated. The initial studies focused on analytical solutions that continue to be the main emphasis of the Sheffield fire research. However, a number of recent projects have involved major physical tests, using unique, purpose-built facilities.

The group has been working for a number of years toward establishing a practical robustness analysis for steel and composite buildings. This is very much in line with the recommendations that were made after the World Trade Center disaster in New York. Efforts are now being directed toward the development of a general performance-based fire resistance design approach, moving away from the current prescriptive rules. Because connections are recognized as the most vulnerable parts of a structure, the state-of-the-art reflects modeling of their behavior as integral elements of the structural models. This is facilitated by progressive failure analyses of the components, incorporating limit states of local or overall building collapse. A significant advance is the development of component-based models of various types of connections that are suitable for use in fire engineering structural analysis. Some current research projects are presented in the following sections.

Design of Beam to Composite Column Connections for Improved Fire Robustness: This is part of the European Union funded project COMPFIRE, a joint effort of the universities of Sheffield and Manchester in England, the University of Coimbra in Portugal (lead institution), Luleå Technological University in Sweden and the Czech Technical University in Prague in the Czech Republic. Additional work is provided by the steel producer Tata Steel Research, Development and Technology. The project director in

Sheffield is Professor Ian Burgess; additional Sheffield researchers are Drs. Buick Davison and S.-S. Huang.

The project addresses the behavior and robustness of practical connections between steel or composite beams and two types of composite columns: concrete-filled tubes and partially encased W-shapes with concrete infilled between the flanges. The Sheffield work includes physical tests of flush end-plate and so-called reverse-channel connections and includes the development of component-based analytical models for such connections. Large rotation tests of full-scale connections have been tested at constant temperatures using combinations of tensile and shear forces. The loading conditions simulate realistic cases for connections in building fires. The scope of the series of tests has provided the basis for a limited parametric study, with experimental data that validate the component-based models. The test setup is shown in Figure 1.

Figure 2 shows two typical test specimens. Figure 3 shows the failure of a reverse-channel connection. The researchers noted that the reverse-channel connection not only provides a practical construction-site solution for connecting steel beams to composite or hollow-section columns, but it also offers significant ductility and high strength when compared to other more conventional connection types, as documented in Figure 4. It is particularly important to note that the high ductility allows the extra connection forces and moments that are normally generated in a fire to be reduced to very low levels; this increases the connection fire resistance without requiring it to be extremely strong. Finally, a component-based finite element model was created for the connection using component characteristics developed in this and previous projects (Spyrou, 2002; Block, 2006; Yu et al., 2009).

Progressive Collapse Modeling of Steel-Framed Structure in Fire: Going beyond the COMPFIRE project, modeling and analysis of progressive collapse has been facilitated with the development of a software package called Vulcan. The research team has the same staffing, with the addition of Professor R.J. Plank. The main objective has

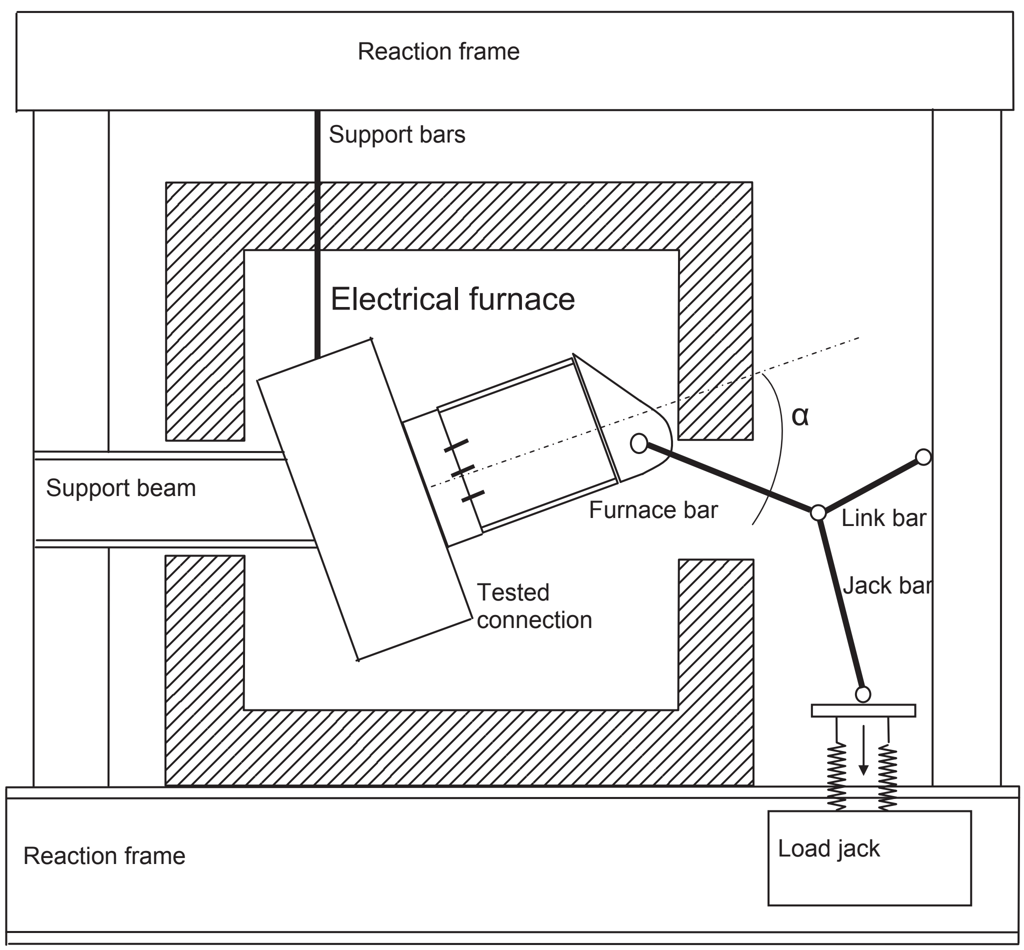
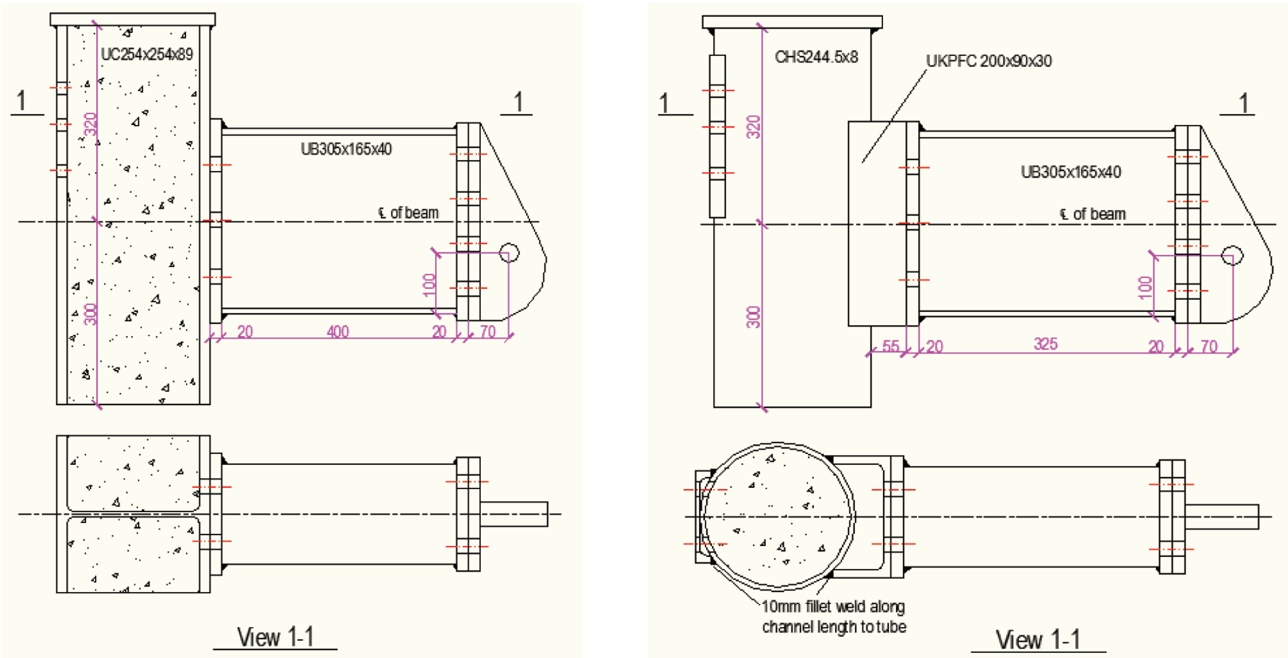


Fig. 1. Fire test setup for a beam-to-column connection (drawing courtesy of Professor Ian Burgess).



(a) (b)

Fig. 2. (a) Flush end-plate test specimen; (b) reverse channel test specimen (drawings courtesy of Professor Ian Burgess).

Fig. 3. Typical failure mode of a reverse-channel connection (photograph courtesy of Professor Ian Burgess).

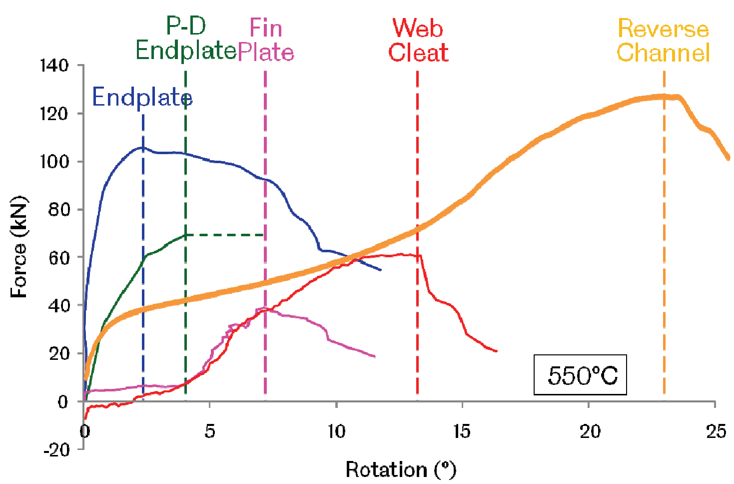


Fig. 4. Force-rotation relationships for various connections at 550 °C (1022 °F) (figure courtesy of Professor Ian Burgess).

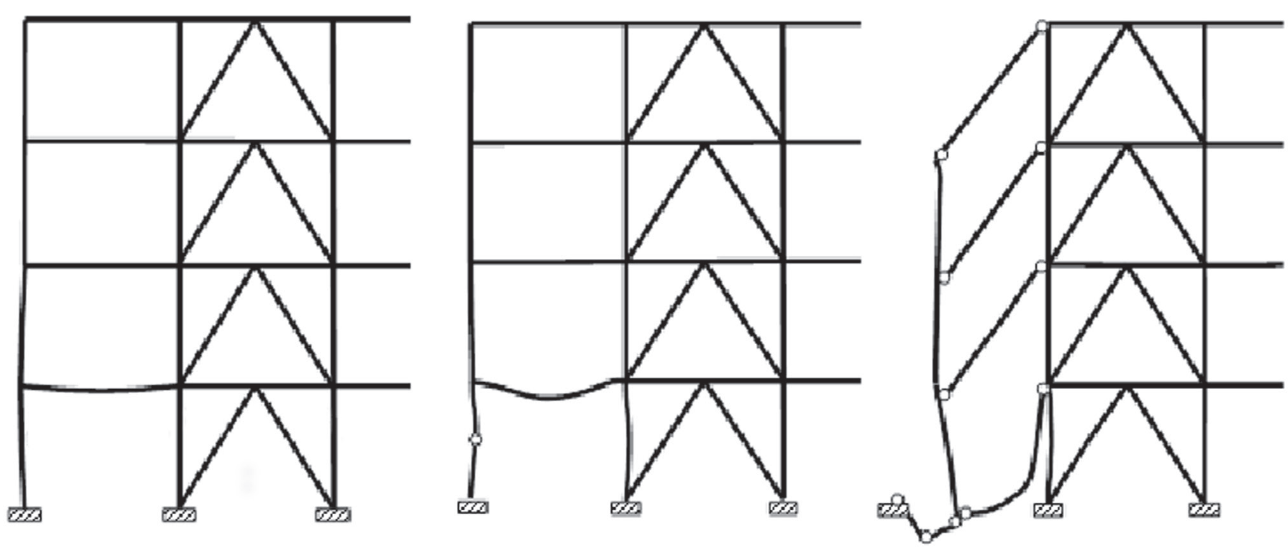
been to develop a practical structural fire engineering analysis approach, allowing for the study of the mechanisms and principal phenomena of the progressive collapse process.

The numerical procedure used incorporates the complete structural behavior, including the progression from local buckling to overall collapse. The model combines alternate static and dynamic analyses as follows: Static analysis is used to trace the behavior of the structure at changing temperature until instability takes place. Beyond this point, a dynamic procedure is activated to track the motion of the system until stability is regained. This has been shown to work well in progressive collapse analyses that incorporate fire scenarios (Sun et al., 2012a). The process specifically allows for the identification of different forms of global failures and severe local failures, determining the sequence of the collapse mechanism. Several factors entering into the fire-induced progressive collapse are identified, including loading level, structural configuration and detailing, and type and location of the bracing system (Sun et al., 2012b). Figure 5 illustrates one such case of progressive collapse at increasing temperature levels.

Dynamic Behavior of Steel Connections with High Strain Rate and Noncyclic Dynamic Loading: Structural connections play a very important role in preventing progressive collapse in impact or explosion situations. Under such conditions, the connections must be capable of resisting high strain rates, meaning that high ductility is critical to help dissipate the energy through deformation without failure. The performance of connections under different types of loading using a wide range of strain rates was the motivation for a series of high-strain-rate tests on simple connections (Lau and Hancock, 1987). An example of a typical failure is shown in Figure 6.

In a follow-up study, numerical modeling was used to analyze the experimental results. Initially, a double-angle connection, which has a relatively complex geometry, was modeled as a base case for the development of other models. This approach has been validated by the experimental data, as illustrated in Figure 7 (p. 200). Additional models are now being developed for different types of connections. Parametric studies will be performed to evaluate the sensitivity of the models to geometric and material variations, particularly with reference to the effects of the strain rate.

Making the Case for Design for Deconstruction: This unique project reflects novel thinking about certain aspects of sustainability. Dr. Buick Davison is the director of the study, which explores what is required of the structural designer to take a structure down at the end of its useful life. Specifically, the study will investigate and quantify the environmental benefits of design for deconstruction. The strategy facilitates future reuse of structural and nonstructural materials by designing buildings to be systematically taken apart with no damage to their components. By reusing materials, the embodied energy and carbon of buildings can be reduced, and fewer natural resources need to be extracted from the earth. Steel is particularly suitable for reuse due to its durability as well as the fact that it is the most recycled of all materials. Steel elements do not necessarily have to be reused because contemporary steelmaking practice feeds recycled material into the steel production process.



(a) 527 °C (b) 698 °C (c) 745 °C

Fig. 5. Progressive collapse mechanisms for a braced frame at increasing temperature (figure courtesy of Professors Ian Burgess and R.J. Plank).

Distortions, deflections and corrosion may have occurred in members during their service life. These effects can be measured, making it relatively simple to assess their suitability for reuse.

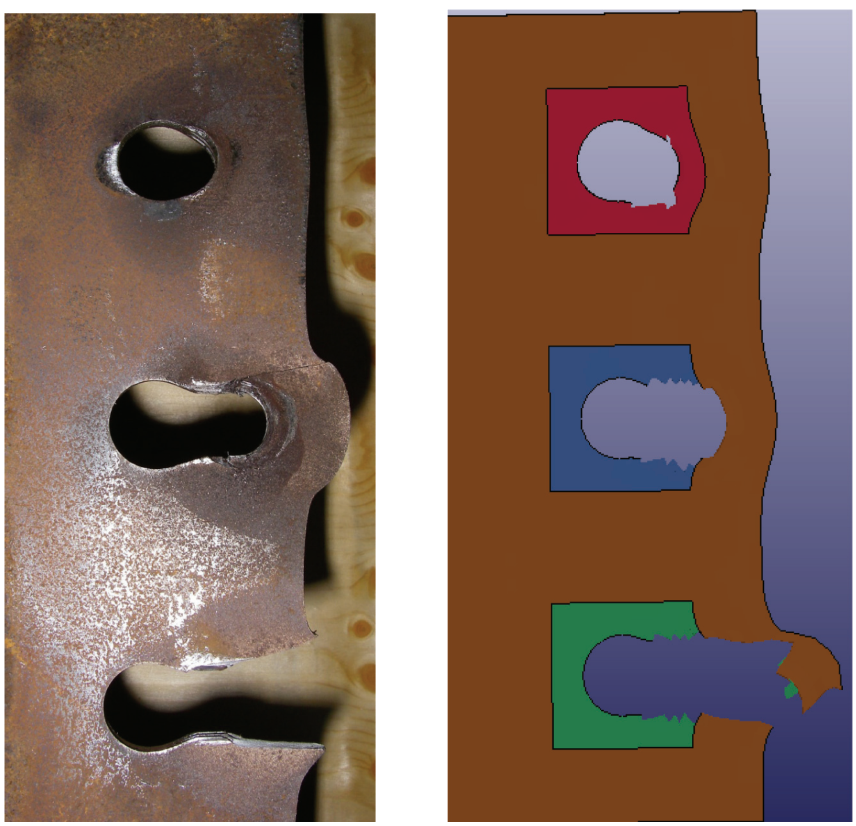
A methodology has been developed to account for designed-in future benefits (Densley Tingley and Davison, 2011a, 2011b). This involves sharing the environmental impact of a component between its predicted number of "structural lives." As an example, the benefits of designing a structural bay for deconstruction have been explored, showing that there can be a 60% increase in the embodied carbon of a structure if it has not been designed for deconstruction. Consequently, a web-based tool has been developed that facilitates calculation of the energy and carbon savings from designing for deconstruction, as well as the subsequent material reuse that will result. Named Sakura, the software allows designers to input information to explore the benefits to a specific project of designing for deconstruction. It is anticipated that the use of Sakura will promote and encourage design for deconstruction where appropriate, thus increasing future supply chains of reused materials and advancing sustainability.

SOME CURRENT RESEARCH WORK AT LULEÅ UNIVERSITY OF TECHNOLOGY IN LULEÅ, SWEDEN

The steel research group at Luleå University of Technology (LTU) is one of the most active in Europe and the only program in Sweden that has chair in steel structures. Professor Milan Veljkovic has been the director since 2007. To increase the relevancy of their work, the researchers include full-time faculty as well as part-time professors from industry and visitors from other countries. Naturally, doctoral candidates are critical to the success of research efforts, and in the last five years the program has grown from 2 to 13 participants. The group's expertise ranges from computational modeling to fire heat transfer to structural analysis and design.

The principal research subjects are:

- Behavior, strength and practical implementation of higher strength steel in construction; in applications for buildings, stadiums and other long span structures; and in towers for wind turbines.



(a) (b)

Fig. 6. Failure of connection details due to high strain rates: (a) actual connection plate; (b) connection detail model (photographs courtesy of Professor Ian Burgess).

- Safety of structures exposed to fire, including fire development, heat transfer from the gas temperature to the structure and post-fire resistance of steel structures.

- Development of design recommendations for innovative bridges, such as composite bridges with integral abutments, where in-situ data are correlated with laboratory results and finite element analyses.

Recent work has added computational modeling of materials as well as stochastic material imperfections.

The group traditionally performs industry-oriented and applied research. Seven of the current eight projects are financed by the European Union. The majority of the projects receive funding from the Research Fund for Coal and Steel, and one is financed within the Framework Program 7, an EU-program for small and medium enterprises. As is now typical for European research efforts, multiple partners from academia and industry in several countries collaborate in each of the EU projects. The research funding to LTU of each project is approximately €100,000 per year.

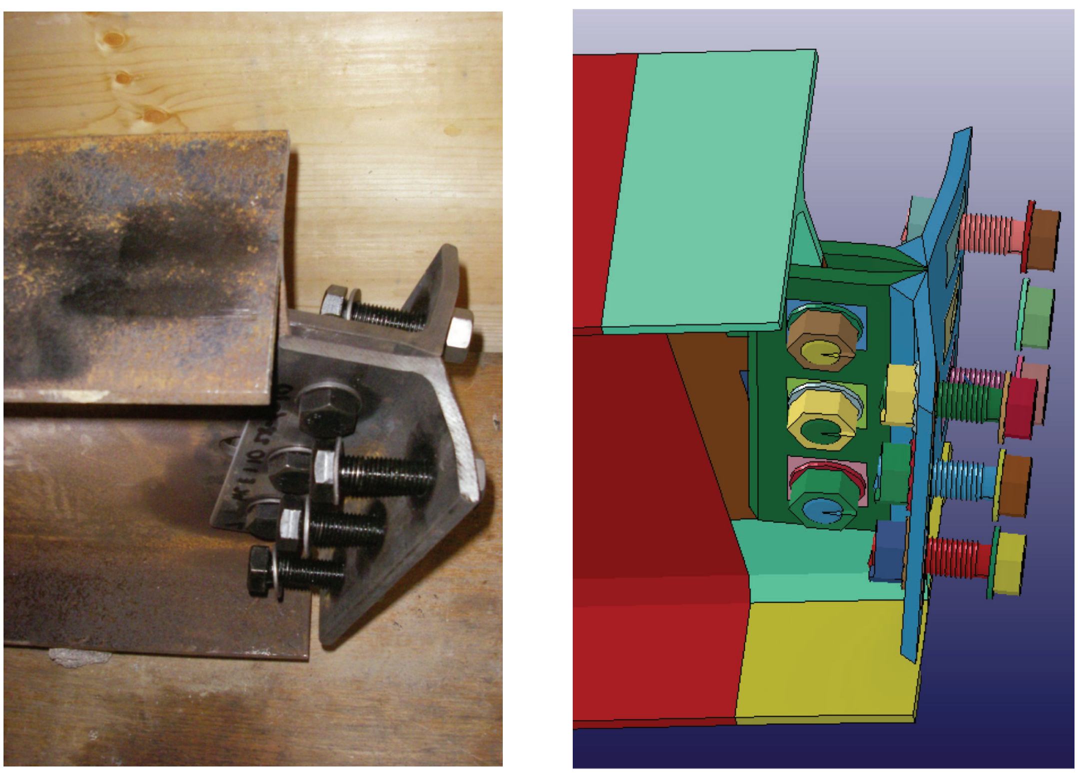
Some of the current projects are described in the following.

High Steel Towers for Wind Turbines (HISTWIN): The first wind tower project was funded for a three-year period from 2006 to 2009. Professor Bernt Johannson (now retired) was the director. The research consortium consisted of Luleå Technological University (lead institution); the Technical University of Aachen (RWTH), Germany; the University of Coimbra, Portugal; Aristotle University of Thessaloniki, Greece; the steel company Rautaruukki OY, Finland; and the energy companies Martifer Energia, Portugal, and GLWind, Germany.

The main objective was to improve the competitiveness of tubular steel wind towers for hub-heights from 267 to 333 feet. The height limitation is required by transportation restrictions that limit the diameter of the bottom segment to about 15 feet. Traditional flange connections (Figure 8a) are labor intensive, expensive and require complex design models. Their fatigue resistance is low and is often the governing design criterion.

A breakthrough was achieved with an innovative solution that uses a slip-resistant connection with open-slotted holes. The idea is illustrated in Figure 8b. A series of small-scale physical tests were used to evaluate the feasibility of fabrication and to test the critical connection. The tests provided input data for finite element analysis and for design.

To facilitate assembly of the tubular sections, the lower segment has long, open-slotted holes, as indicated in Figure 8b. The bolts can be preinstalled in the standard holes in the upper section and then used for the angular alignment



(a) *(b)*

Fig. 7. (a) Deformed angles of the physical test; (b) connection model (photographs courtesy of Professor Ian Burgess).

while the upper segment slides down. Slots weaken the lower section, giving lower sensitivity to assembly tolerances. The bending stiffness of the tubular shell is enhanced by the overlapping connection. Essentially, this connection allows for tight contact between the cylinders of the upper and lower tubular segments. Lastly, instead of using standard washers for each bolt, a common cover plate solution has been developed. Its purpose is to hold the bolt group together during assembly and to distribute the clamping force in a more uniform manner.

High Steel Towers for Wind Turbines—Second Project (HISTWIN 2): Due to the overall scope of the tubular wind tower project, it was decided that a follow-up project was needed. The funding period was three years, from 2010 to 2013. The academic and industry partners were the same as the first project, and Professor Milan Veljkovic was appointed project director.

The issue of local stability had been identified as critical to the success of the HISTWIN projects. To address this concern, the distances between the bolts in longitudinal connections and between modular segments have to be optimized. Numerical analysis and physical testing will be used to evaluate the effects on longitudinal bolted connections.

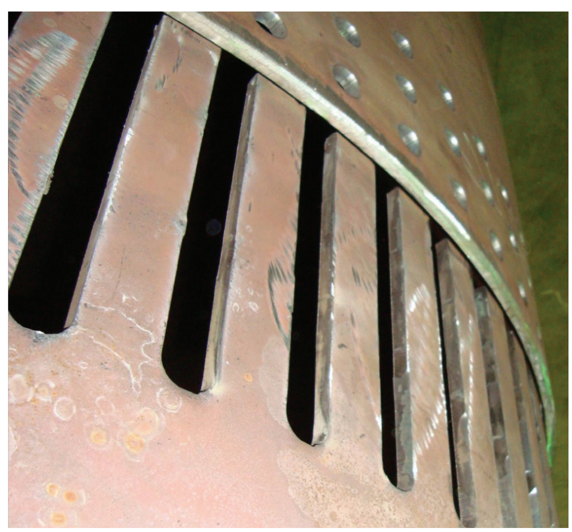
In the early segments of the project, it became clear that the stability issue would be more important for towers with slip-resistant connections. This subject is currently being addressed by considering alternative cross-sections. For example, using various numbers of folds to create a polygonal cross-section offers an attractive solution. Also, the foundations for the towers are critical, considering where the towers will be placed in the ocean. Traditional concrete slab foundations currently used in most onshore wind farms are not adequate for higher towers. A new type of hybrid slab foundation anchored with steel micro-piles has been developed, and this solution appears to offer significant advantages.

Optimization of Frames for Effective Assembly (Project FRAMEUP): The project is funded by the European Union's Research Fund for Coal and Steel for the period from 2011 to 2014. The research consortium consists of Luleå Technological University (lead institution); the University of Liège, Belgium; the Technical University of Aachen (RWTH), Germany; the University of Coimbra, Portugal; Aristotle University of Thessaloniki, Greece; and the construction companies Acciona Infrastructures S.A., Spain, PartConstruction AB, Sweden, and V&M Deutschland GmbH, Germany.

The three main objectives of the project are:

- *To develop the concept of a design process for a structural system primarily used for buildings with prefabricated steel 3D modules.* The process will be tested by computer simulations using a virtual engineering tool. Such a tool allows for the identification of all possible conflicts in the design, including the transfer of modules from delivery trucks to the structure. This is an integral part of the new design process. The procedure starts with the assembly of the roof and the top floor, providing a stiff structure that will be lifted by jacks. Each story will be assembled at the ground level and then lifted up to create space for the next story. This protects every story from precipitation and other moisture damage during the assembly. The process is based on using jacks

(a)



(b)

Fig. 8. Wind turbine tower connections: (a) traditional flange connection; (b) slip-resistant connection (photographs courtesy of Professor Milan Veljkovic).

instead of cranes and is expected to be safer and drier. The construction site will also be smaller, with less noise and other disturbances for its neighbors. An example is shown in Figure 9.

- *To test and establish the performance of a new type of connection that uses a number of nonstandardized components.* The connections are developed for HSS columns and beams. They must satisfy the requirements for faster assembly and disassembly as well as the requirements for moment resistance specified by local design codes.

- *To achieve an optimized building technology with 3D modules using the innovative erection technique.* This is influenced by the architectural demands, which in turn influence the structural solution.

Design of Connections to Composite Columns for Improved Fire Robustness (COMPFIRE): This project is in partnership with the University of Sheffield, previously discussed.

Other Projects: Projects on High-Strength Long-Span Structures (HILONG) and Rules On High-Strength Steel (ROUSTE) have been approved for 2012 through 2015. Studies on composite bridge construction were conducted in the project Economic and Durable Design of Composite Bridges with Integral Abutments (INTAB+) and completed in 2011. Papers and reports are currently being prepared.

Significant educational efforts will also be pursued during the 2012 through 2015 time period, addressing the broad subject of sustainable structures under natural hazards and catastrophic events. These projects are funded by the European Union under the Erasmus Mundus educational program. Six universities are partnering for this activity.

SOME CURRENT RESEARCH WORK AT THE UNIVERSITY OF TRENTO IN TRENTO, ITALY

The structural engineering research group at the University of Trento was established in 1985 when the Faculty of Engineering was founded. Since the very beginning, the group has been active in the fields of steel and wood construction, generally associated with earthquake engineering. Most recently, the fields of smart structures and structural monitoring and control have been explored.

The research group has seven faculty members related to steel structures. Their current activities focus on three main areas of research:

- Dynamic and seismic response of steel and composite (steel-concrete) structural systems.

- Stability of complex engineering systems.

- Structural robustness.

In addition, the group is heavily involved in industry-based research projects. These projects include a nearly 20-year effort supporting Italian rack manufacturers. The

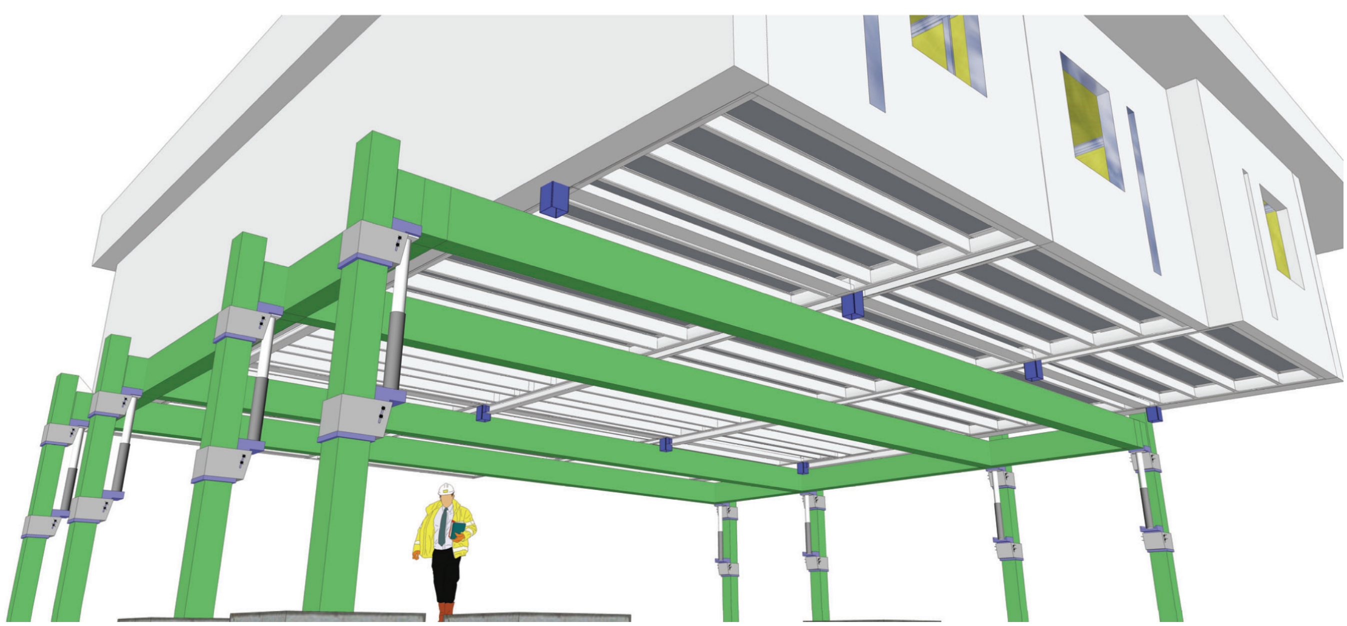


Fig. 9. Erection phase of the FRAMEUP pilot building (figure courtesy of Professor Milan Veljkovic).

knowledge gained from rack research related to the performance of cold-formed systems led the group to develop a new prefabricated system for residential steel housing.

Extensive experimental facilities provide great flexibility in accommodating complex tests under static and dynamic loading, including full-scale specimens. The group is also active with Italian and European code committees, as well the committees of the European Convention for Constructional Steelwork (ECCS). A discussion of several of their current research projects follows.

Design and Integrity Assessment of High-Strength Tubular Structures for Extreme Loading Conditions (HITUBES): Funded by the European Union's Research Fund for Coal and Steel with the University of Trento as the lead institution, Professor Oreste Bursi is the project director. The project partners are the University of Liège, Belgium; the University of Thessaloniki, Greece; the Italian Center for Materials Development; the Portuguese Institute for Welding and Quality; the ITMA Foundation of Spain; and the Corrosion and Metals Research Institute of Sweden.

The HITUBES project was recently completed. The project goal was to develop performance-based design and assessment procedures for the use of high-strength steel tubes in a variety of applications, in steel grades as high as S700MC (a yield stress of 700 MPa or 100 ksi). The use of tubes in structures subjected to extreme repeated loads was also examined. The project's ambitious goals included increasing structural performance, reducing structural weight, and reducing construction and operating costs. Specifically, the following subjects were addressed:

- Structural identification and health monitoring of cable-stayed and arch footbridges.
- Simulation of welded and bolted connections under monotonic, low-cycle and high-cycle fatigue loadings.
- Reliability analysis for quantification of realistic performance scenarios.

Two types of structures were analyzed in detail for possible construction with steel tubes: slender pedestrian and bicycle bridges and the arch and hanger elements of railway bridges. Railway bridges in particular are commonly subjected to extreme repeated loads.

The Trento contribution was mainly associated with the dynamic identification and the finite element model updating. Reference was made to the Ponte del Mare, the bridge shown in Figure 10, which is a twin-deck, curved, cable-stayed pedestrian bridge. The outer deck is reserved for pedestrians, while the inner deck is for bicyclists. The decks have constant radii of approximately 267 feet and 330 feet.

The pedestrian bridge was redesigned using circular hollow sections in steel grade TS 590 (a yield stress of 590 MPa or 85 ksi). In the redesign, the high-strength steel and the circular cross-sections combine to reduce the visual impact of the bridge and to reduce the structure's weight. The research included both design and in-situ testing of the bridge. A comprehensive numerical analysis showed that a passive control system made of elastic and viscous-fluid dampers was necessary to mitigate pedestrian vibrations and to satisfy wind safety requirements relative to premature aero-elastic instability.

Performance-Based Approaches for High-Strength Tubular Columns and Connections under Earthquake and Fire Loads (ATTEL): The project is also funded by the Research Fund for Coal and Steel, with the University of Liège as the lead institution. The international partners are the University of Trento and the University of Thessaloniki, Greece, with industry partners the Italian Center for Materials Development and Italian fabricator Pichler. The Trento group is coordinated by Professor Oreste Bursi.

A capacity design approach, in which structures are designed to meet the strong column–weak beam concept, is usually achieved by overdesigning the columns. A substantial improvement to the structural performance using this approach may be achieved by the use of high-strength steel, provided the steel and the detailing meet ductility and energy absorption criteria. The adoption of high-strength circular hollow sections for such purposes has been limited, despite excellent structural properties. Even recent Eurocode 3 modifications permitting the use of steel grades up to 700 MPa (100 ksi) maintain strict limitations at the material, structural and design levels (ECCS, 2005, 2007).

The ATTEL project aims to provide the analytical and experimental knowledge necessary to develop design criteria for the high-strength steel and composite circular hollow sections for columns and connections subjected to seismic and fire loads. The focus is on structural tubes ranging from 7 in. to 14 in. in diameter with a *D/t* ratio greater than 30. This range is of great interest for onshore structures. The following subjects are addressed:

- Steel and concrete-filled tubular (CFT) columns made of high-strength steel.
- Welded or bolted composite beam-to-CFT column connections in high-strength steel.
- CFT column base connections made of high-strength steel.

In Trento, the study has focused on the cyclic performance both of column base connections for tubular composite columns and beam-to-column connections (Zanon et al., 2011). The first series of tests on standard and innovative column base connection solutions are shown in Figures 11 and 12. Both standard and innovative seismic connections exhibited favorable hysteretic response without loss of strength and stiffness.

Stability of Industrial Steel Pallet Racks: Industrial racks are one of the most common structures for storing palletized goods. Examples of such structures are shown in Figure 13. A number of studies were carried out under the supervision of Professors Nadia Baldassino and Riccardo Zandonini to investigate key aspects of the performance of such systems.

Rack structures use thin-walled cold-formed steel shapes and, for this and many other reasons, exhibit very complex behavior. The main sources of complexity are the sensitivity of the columns (uprights) to buckling, the presence of perforations on the uprights that provide for the attachment of beams, the non-linear response of the connections, the frame sensitivity to the second-order effects and the influence of imperfections. The large variability in the geometry of the shapes, of the joints and of the perforations combined with the complexities of member behavior cannot be incorporated into practical design provisions at this time. Tests—preferably full-scale tests—are needed.

Relevant codes recognize the concept of design by testing and provide detailed recommendations for the testing of members, subsystems and joints (AISI, 2007). A thorough analysis of Eurocode 3 (ECS, 2005) identified a number of issues that are not adequately addressed (Baldassino and Zandonini, 2011). This triggered several studies of the buckling of perforated members, of base-plate connections and of the shear stiffness of upright frames.

The most recent work relates to the upright frames that typically ensure the stability of pallet racks in the cross-aisle direction (Gilbert et al., 2012). These frames are sensitive to second-order effects, and an accurate determination of their shear stiffness is essential for seismic design and

Fig. 10. The Ponte del Mare, a pedestrian and bicycle bridge in Pescara, Italy (photograph courtesy of Professor Oreste Bursi).

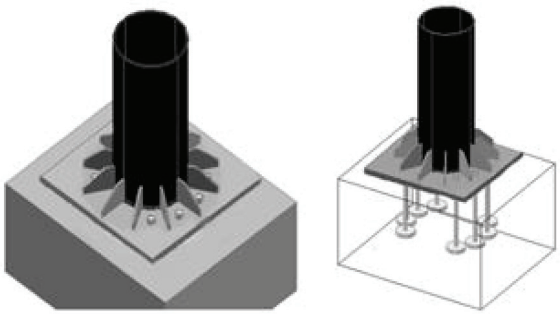


Fig. 11. Standard solution for a column base connection (courtesy of Professor Oreste Bursi).

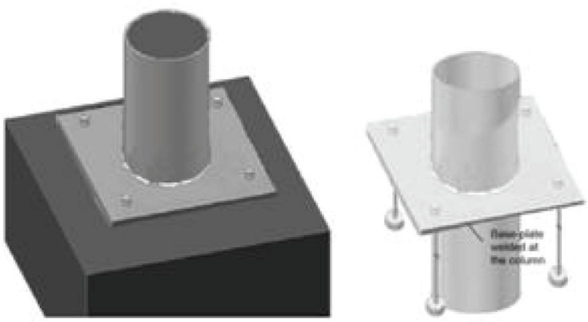


Fig. 12. Innovative solution for a column base connection (courtesy of Professor Oreste Bursi).

to ensure the stability of the rack, especially in the case of high-bay racks and racks supporting the building enclosure. The study compared two alternative methods, one of which is specified by the Eurocode, 3 and the other by the Australian standard. Figure 14 shows the assemblies of the two tests, as performed at the University of Sydney. A total of 36 tests of different frame configurations were performed, including numerical analyses to assess the accuracy of the two methods. The preliminary results show that the shear stiffness determined by these methods may vary by as much as a factor of two. Additional work will be pursued.

Base-Plate Connections for Rack Structures: Column base connections of rack frames are unique, and their response is significantly different from the corresponding connections in traditional steel frames. In Italian practice, the base connections are typically built up from base-plate elements that are bolted to the uprights and connected to the floor by means of special fixing systems. Figure 15 shows some representative examples.

Structural Robustness of Composite Frames: This project is funded by the European Union's Research Fund for Coal and Steel, as a joint effort between the University of Stuttgart, Germany (lead institution) and the University of Trento. Professor Ulrike Kuhlmann of the University of Stuttgart is the project director; Professor Riccardo Zandonini is the Trento coordinator.

Despite studies on robustness that began in the 1960s, only general strategies to achieve effective robust structural

Fig. 13. Typical steel storage pallet rack systems (photographs courtesy of Professors Nadia Baldassino and Riccardo Zandonini).

designs have been established. Recent failures have demonstrated the inadequacy of traditional design approaches when collapse has resulted from local damage caused by human accidental actions. Such issues call for design methodologies that allow verification of the safety of the structure in the statically modified condition so that local damage does not produce a chain reaction that may lead to partial or complete progressive collapse of the structure.

The tests conducted at the University of Trento were aimed at determining the performance of both the concrete slab and the steel connection, in accordance with the component method of connection design as specified by Eurocode 3 (ECS, 2005). In particular, the study focused on the response of connections subjected to combined axial, shear and moment stress resultants, as illustrated in Figure 16, and on T-stub components under combined axial and shear forces (Baldassino and Zandonini, 2009).

The testing assembly shown in Figure 17 was specifically designed to apply a wide range of axial and shear forces to the T-stub. By changing the location where the testing assembly is connected, it is possible to simulate rotation of the T-stub with respect to the load line. This rotation effectively allows for the application of different combinations of axial and shear forces, ranging from pure tension to pure shear. The tests on the full connection demonstrated the negative influence on both the ultimate load and deformation capacities of a loading history that combines shear, moment and axial force. The T-stub tests provided the data for the shear and axial force interaction domains. Both series confirmed the inherent high ductility.

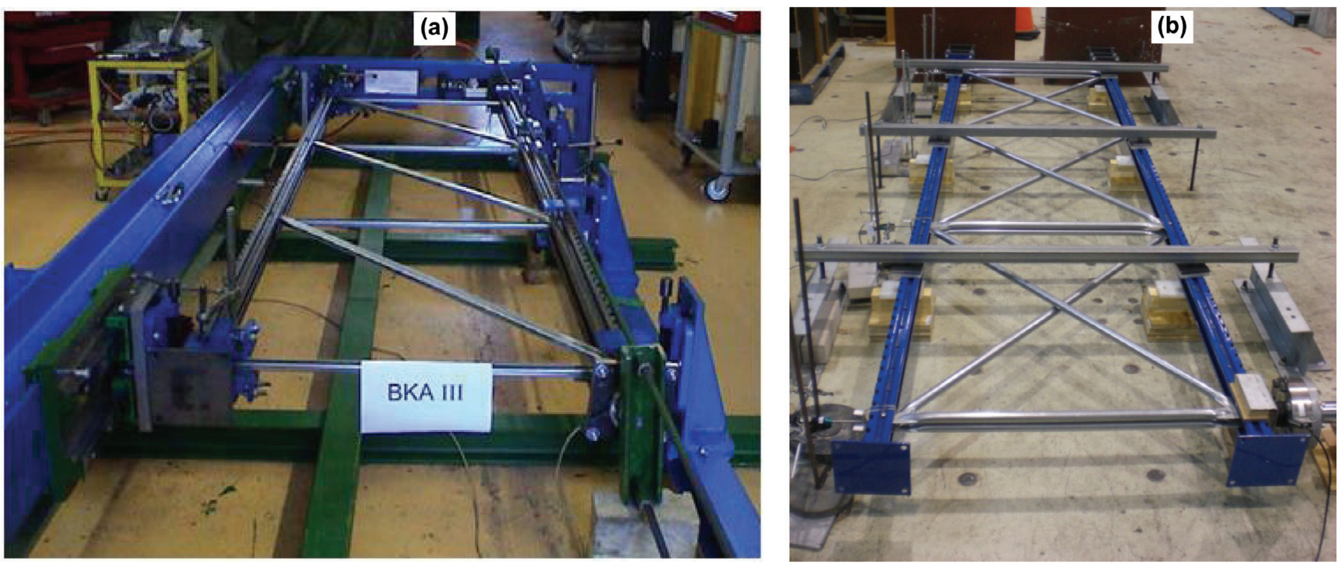


Fig. 14. Shear tests on upright frames: (a) Eurocode 3 method; (b) Australian standards method (photographs courtesy of Professor K.J.R. Rasmussen).

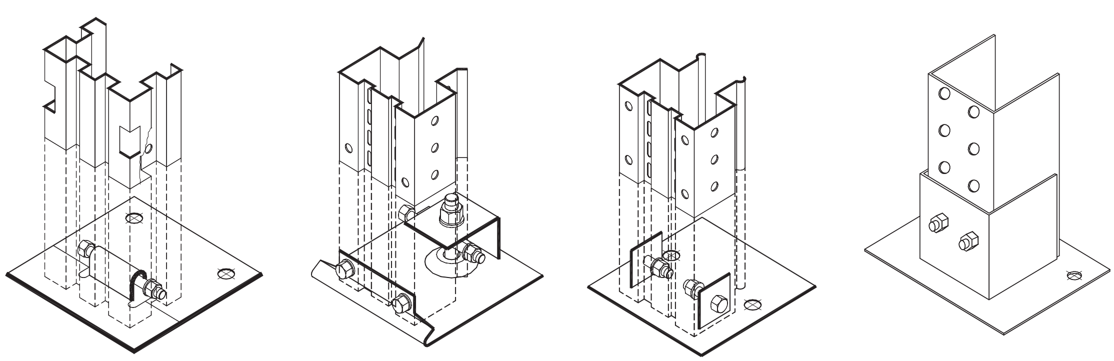
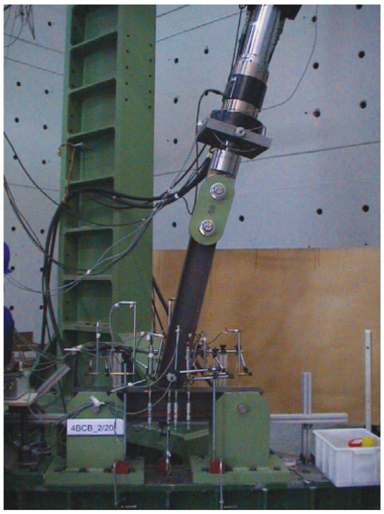


Fig. 15. Typical base connection details for Italian rack structures (figures courtesy of Professors Nadia Baldassino and Riccardo Zandonini).

A second project, about to start with the same partners, will primarily examine 3D action and the strain rate effect. The University of Trento will perform two full-scale tests on a flooring system as shown in Figure 18 to investigate the strain-rate effect on the T-stub response.

ACKNOWLEDGMENTS

Significant assistance has been provided by ISSRA member Professor Riccardo Zandonini of the University of Trento, and by his colleagues Professors Nadia Baldassino and Oreste Bursi. Professor Ian Burgess of the University



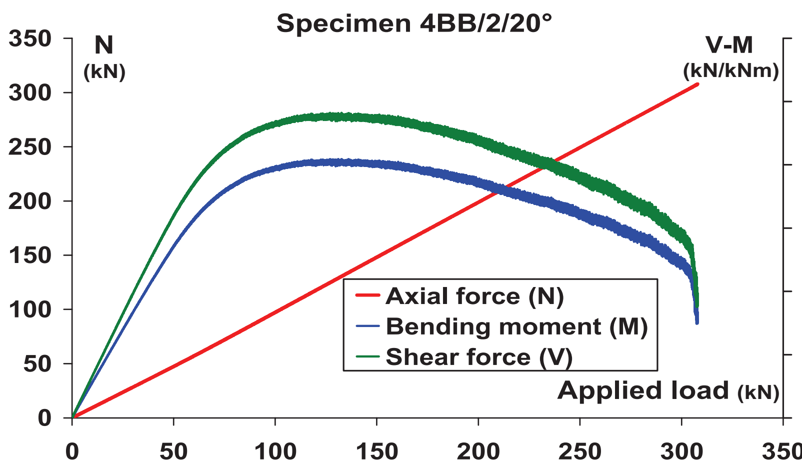
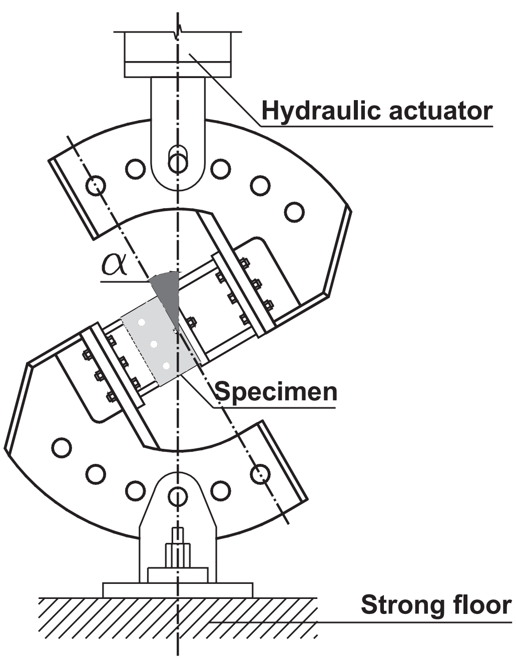


Fig. 16. Test on beam-to-column connection under combined axial and shear forces (figures courtesy of Professors Nadia Baldassino and Riccardo Zandonini).



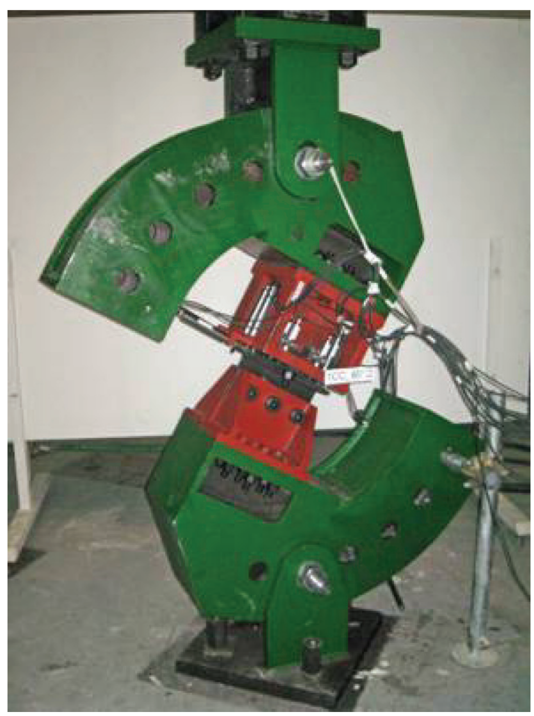


Fig. 17. Test set-up for T-stub tests under axial and shear force (figures courtesy of Professors Nadia Baldassino and Riccardo Zandonini).

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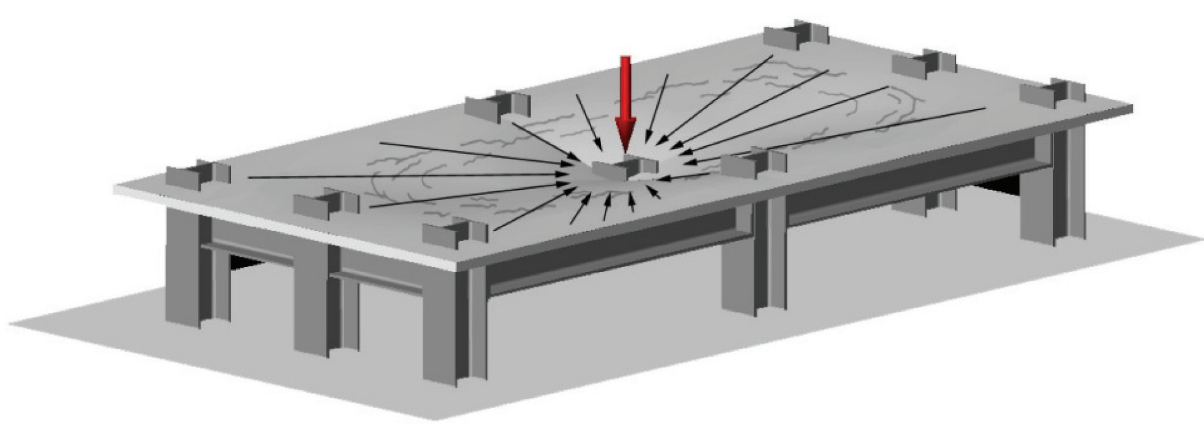

Fig. 18. Full-scale test on a floor system simulating the collapse of a column (figure courtesy of Professors Nadia Baldassino and Riccardo Zandonini).