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INTRODUCTION

This issue of "Current Steel Structures Research" for the *Engineering Journal* focuses on a selection of research projects at two French language universities: one from Canada and the other from France. The descriptions will not discuss all of the current projects at the schools—there are too many. But selected studies provide a representative picture of the research work and demonstrate the importance of the schools to their countries and their impact on industry and the profession worldwide.

The universities and their researchers and graduate students are well known in the world of steel construction: the École Polytechnique in Montréal, Quebec, Canada, and the National Institute of Applied Sciences of Rennes in Brittany, France. In France, the latter is normally referred to as INSA–Rennes (Institut National des Sciences Appliquées de Rennes). There are several INSAs in France, all of which are powerful centers of advanced study in engineering and applied science.

The sizes of the civil engineering faculties in general—and, especially, the structural engineering groups—are essential for these institutions. The studies that are presented in the next sections describe elements of the projects as well as other long-time efforts. As has been typical of American and European—and indeed worldwide—engineering research projects for years, many of the projects are multi-year; a number are also multi-partner and some are also multi-country efforts. The outcomes of the projects focus on industry needs and implementation in design standards.

The researchers in Montréal and Rennes have been active for many years, as evidenced by their leading roles in research and development in Canada, the United States and Europe, but they have also been frequent participants in the work in other countries and regions. Numerous high-quality papers, reports, design guides and conference presentations have been published, contributing to a collection of studies that continue to offer solutions to complex problems for designers as well as fabricators and erectors.

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

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SOME CURRENT RESEARCH WORK AT ÉCOLE POLYTECHNIQUE OF MONTRÉAL

A broad discussion of some of the ongoing research work in the Department of Civil Engineering at École Polytechnique of Montréal (ÉPM) was presented in the Fourth Quarter 2013 issue of the *Engineering Journal* (Bjorhovde, 2013). However, it was not possible to include a number of important projects at that time, and these are detailed in this paper.

Collapse Prevention of Low Ductility Concentrically Braced Frames

This is a collaborative research project led by Professors Larry Fahnestock of the University of Illinois at Urbana-Champaign and Eric Hines of Tufts University in Boston. It addresses the seismic performance of low-ductility steel braced frames designed with R = 3.0 and located in low and moderate seismic regions. The objectives of the project are to develop a fundamental understanding of the seismic performance of such structures. Further, it is essential to increase their reliability and resistance to seismic collapse by accounting for existing lateral capacity or to provide enhanced reserve capacity. In low-ductility braced frames, the failure of brace connections in tension is likely to occur early during a strong earthquake, prior to brace buckling in compression and yielding in tension. This can result in significant loss in lateral strength and stiffness and may lead to frame dynamic instability (Hines, Appel and Cheever, 2009). Upon reversal of loading, braces at failed connections may re-engage in bearing, as shown for a slotted HSS connection in Figure 1a. This behavior is generally ignored in seismic collapse assessment analysis. One means of enhancing reserve capacity of the frames is to introduce partial-strength beam-to-column connections with top and seat angles in the gravity frame of the building, as illustrated in Figure 1b. Nonlinear time-history analyses have shown that the moment frame action that develops in the gravity frame and the compression response of the braces after brace connection failures can contribute significantly to collapse prevention (Fell et al., 2009; Fell and Kanvinde, 2010).

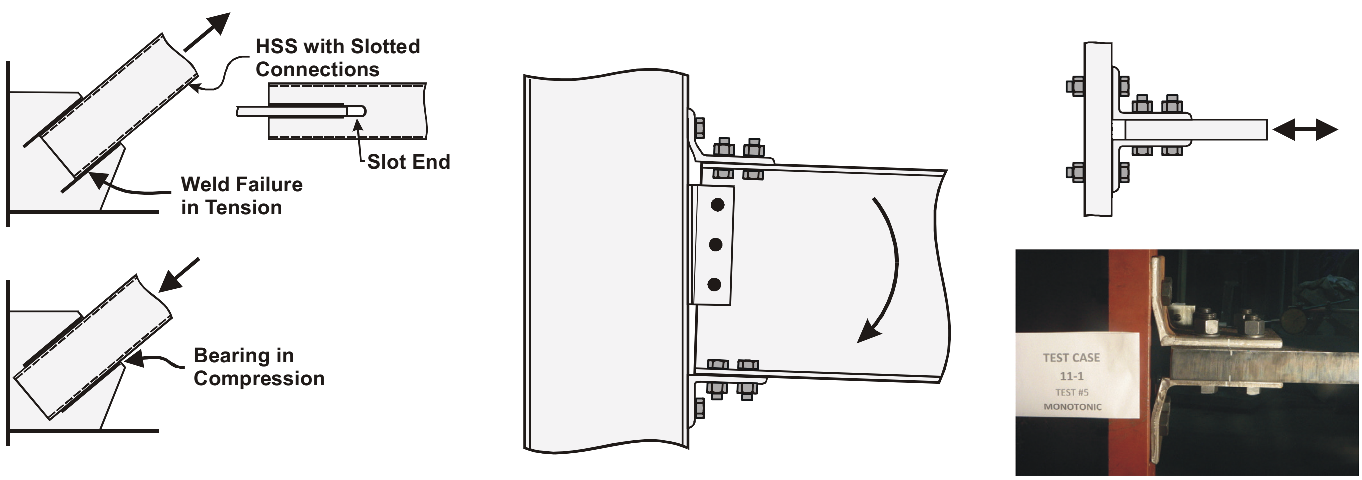
As part of this project, a test program is being performed at ÉPM on beam-to-column connections with bolted web, top and seat angles. Cyclic push-pull static and dynamic tests are performed on isolated angles of various sizes and bolt diameters and patterns. The aim is to develop simple numerical models that are capable of predicting the hysteretic moment-rotation response of the beam-to-column connections, as illustrated in Figure 1c. The model accounts for the contribution of the beam web angles as well as fracture of the angles at large-story drifts. The test program also includes cyclic quasi-static testing of full-scale beam-to-column connections to further validate the numerical joint models. A parallel test program has been developed to generate data on the ductility capacity of welded brace slotted connections and the brace compression response after weld failure. A later phase of the project will test full-scale two-story and half-scale four-story braced frames at the Lehigh University RTMD NEES testing facility.

Shaking Table Testing of Advanced Seismic Force Resisting Systems

New cost-effective systems to achieve superior seismic performance compared to conventional seismic force resisting systems are now being studied. The work has focused on steel-braced frames designed to obtain uniform drift demand over the frame height, to minimize floor accelerations and permanent deformations and to confine any structural damage to easily replaceable components. The solutions generally include elastic braced-frame segments that are interconnected by means of conventional or advanced energy dissipating components such as ductile shear links, buckling restrained braces, self-centering braces and viscous dampers.

One braced-frame configuration currently being studied is illustrated in Figure 2a. It includes four-story elastic braced-frame modules that are linked together and to an exterior column using dedicated energy dissipating elements. Rocking response at the base or over the frame height is also studied. For a given typology, research essentially consists of performing numerical seismic simulations to understand the system response, refining the original concept and eventually developing simplified methods for its design. In the process, experimental validation may be needed to validate the numerical predictions, especially when the response involves complex dynamic phenomena such as sudden increases in stiffness induced by contacts or impacts, rapid strength and stiffness degradation behavior, dynamic instability, higher mode response in the inelastic range or components exhibiting nonlinear rate dependencies. Such validations generally need to be performed at the global system level so that the interaction between the various components is present, as would be the case in actual structures. This can be achieved using shaking table tests on reduced-scale models or real-time hybrid simulations with physical substructures that reproduce the critical phenomena.

Taking advantage of the 36-ft clear test height and the high overturning moment capacity of the earthquake simulator at ÉPM, a unique reconfigurable test setup was constructed over the last five years to perform shaking table testing of structural models up to eight stories. The setup includes a gravity/mass system that emulates the tributary floor seismic masses and weights for the lateral load resisting system being tested on the shaking table.



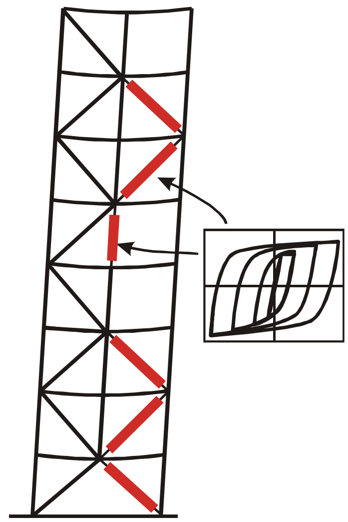
(a) (b) (c)

Fig. 1 (a) Re-engagement of a bracing member after weld failure in tension; (b) rotation demand; and (c) tests on isolated angles for beam-to-column connections with web, top and seat angles in the gravity system of low-ductility CBF structures (figures courtesy of Professor Robert Tremblay).

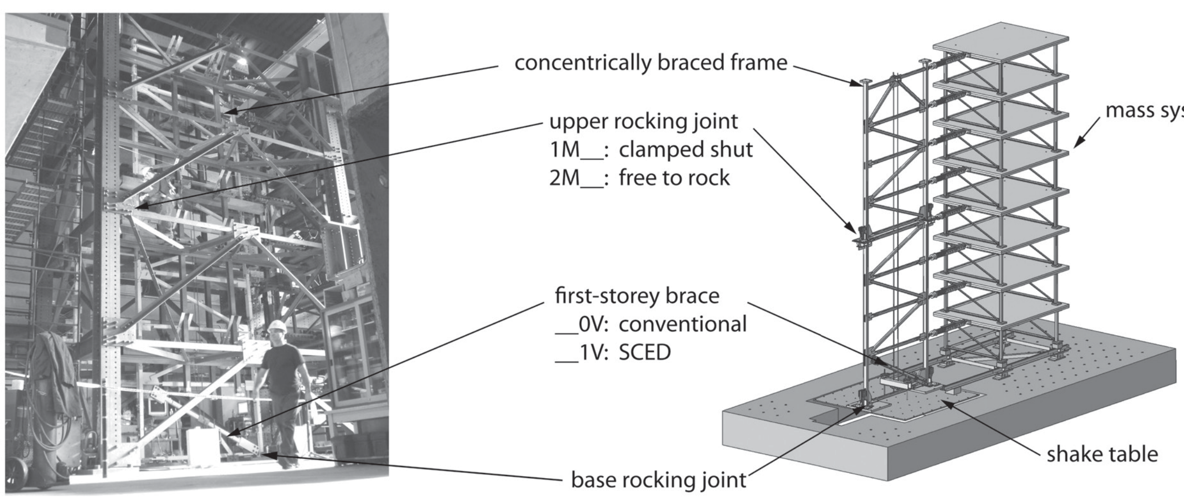
Figure 2b shows the setup that was recently used in a project with Professor Constantin Christopoulos of the University of Toronto for an eight-story braced frame. The frame was designed with two rocking interfaces and a self-centering brace fuse at the first level (Wiebe et al., 2013). As shown in this figure and in Figure 1, the mass/weight system is located on the laboratory ground floor, next to the earthquake simulator, so that the full payload capacity of the equipment is available for the testing. *P*-Δ effects are included in the tests and direct measurements of the applied inertia forces are obtained through the instrumented rigid arms connecting the masses to the specimen. In the future, it is planned to use the setup for similar test programs on other advanced steel seismic force resisting systems.

Future Experimental Research on Column Buckling under Seismic Demand

The potential for column instability under gravity plus seismically induced axial compression and flexural demands represents an important issue in several current research projects. This is the case for columns in multi-story braced frames where the primary axial load demand from gravity loads and brace axial forces is accompanied by in-plane flexural demand from the frame response. Large drifts develop due to the stiffness of the beam-to-columns connections where braces connect to columns, with unavoidable differences in drifts between adjacent stories. Both effects are schematically illustrated in Figure 3. While peak



(a)



(b)

Fig. 2 (a) Innovative steel-braced frame for enhanced seismic performance; (b) reconfigurable shaking table setup for seismic testing of a rocking-braced steel frame with a base self-centering brace shear fuse (figures courtesy of Professor Robert Tremblay).

axial forces in columns of braced frames can be safely predicted by applying capacity design principles, the moment demand can only be assessed using nonlinear response history analysis as it depends on the amplitude and distribution of the frame inelastic deformations during earthquakes. Recent studies of multi-tiered braced frames used in tall single-story structures have been found to be particularly prone to pronounced variations of drifts over their height (Imanpour et al., 2013). Similar behavior is observed in moment frames and eccentrically braced frames with link-to-column connections. For such frames, the flexural demand from the beams or links can be determined from capacity design methods, but the prediction of column bending due to uneven story drifts remains a challenge for design. This response may lead to uneven distribution of the bending moments below and above the beam-to-column connections and the points of inflection that are far from the column mid-height, as is generally assumed in design.

Cyclic testing by Newell and Uang (2008) showed that stocky, fixed-ended W14 columns meeting the AISC section seismic compactness limits could develop plastic hinges at their ends without overall buckling, even when carrying high compressive loads. This suggests that excessive flexural demands on such columns can be accommodated through ductile inelastic flexural deformations. Numerical simulations indicate, however, that column buckling may be triggered when flexural demand not considered in design is applied to columns. As an example, this could be the case for slender columns subjected to flexure approaching single curvature.

Deep columns bent about their strong axis may also fail by lateral-torsional buckling. Buckling of gravity columns due to bending moments induced by large-story drifts concentrating in a given floor is another possible column stability failure example. This situation, which is not covered in current design provisions, may control the lateral deformation capacity of frames.

Column instability due to seismic effects is a complex problem as the axial and flexural demands are cyclic and vary in time, not necessarily in phase, and they are induced by a combination of loads and inelastic displacements. Further, column buckling typically involves large plastic deformations and local buckling. As part of this project, column testing is being planned at ÉPM to complement and validate current numerical work. In collaboration with Professor Charles-Philippe Lamarche of Sherbrooke University, tests will be performed on braced-frame columns with deep columns for moment frames. These studies are done in collaboration with Professor Dimitrios Lignos of McGill University and for columns of multi-tiered braced frames and gravity columns with Professors Larry Fahnestock of the University of Illinois and Christopher Stoakes of the University of Iowa. Realistic axial and uni- or bi-directional flexural demands will be applied to column specimens with the multi-axis loading apparatus shown in Figure 1, using either pre-defined protocols established from nonlinear response history analysis of prototype buildings or from hybrid simulation techniques.

SOME CURRENT RESEARCH WORK AT THE NATIONAL INSTITUTE OF APPLIED SCIENCE IN RENNES, FRANCE

Between 2002 and 2010, the French National Research Project MIKTI was undertaken to develop methods of analysis and design for composite bridges of small and medium spans. Under the leadership of department chair Professor Mohammed Hjiaj and project director Alain Lachal, the contribution of the Structural Engineering Research Group at INSA–Rennes was a major factor in the success of this project. Working in close collaboration with SNCF, the French national railroad organization, and with the companies ArcelorMittal and Vinci, the primary efforts focused on two topics: (1) innovative and economical solutions for continuous beams of composite bridges and (2) the mechanical behavior of groups of headed stud shear connectors with prefabricated slab and steel girders.

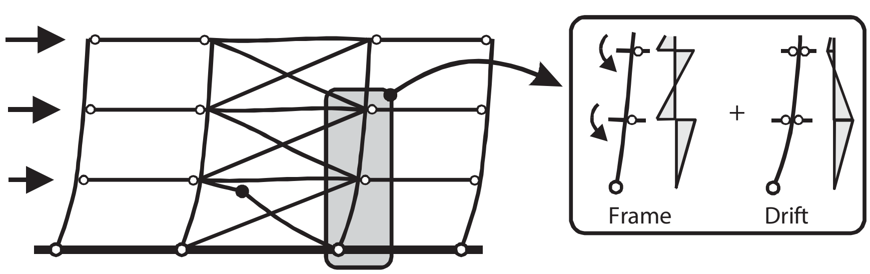


Fig. 3 In-plane flexural demand on columns of steel braced frames. Pinned column bases are shown for simplicity (figures courtesy of Professor Robert Tremblay).

Innovative Connection Solutions

For composite bridges of small and medium spans, the choice of a multi-beam deck with hot-rolled shapes connected to a reinforced concrete slab often appears to be an effective, economical, simple and fast solution for implementation on site. When the total length of the structure exceeds the limit for transport and handling, a beam-to-beam connection on site is necessary to ensure the continuity of the deck.

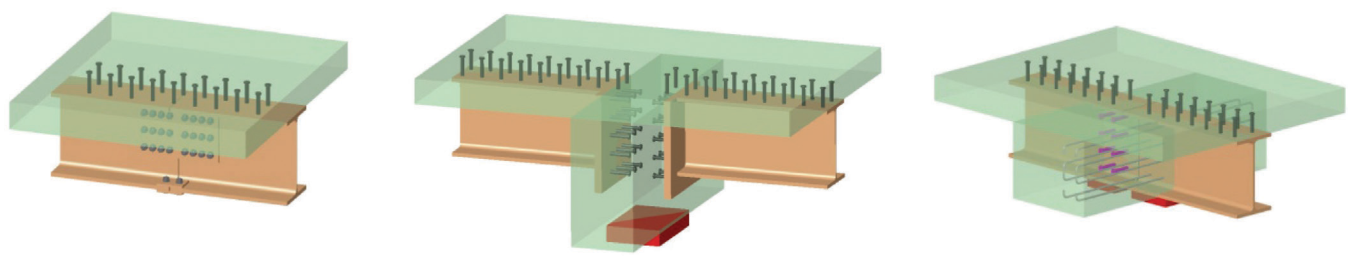
Three continuous joint solutions were selected, as shown in Figure 4. The first solutions uses bolted web cover plates and a direct contact between the compressed bottom flanges of the steel girders. The second solution uses butt plates anchored in the side faces of a transverse bridge piece of reinforced concrete. The third solution uses complete embedding of the two steel girder ends of the composite beam in a massive reinforced concrete transverse beam. Direct contact between the compressed steel girder flanges was also introduced in the third solution.

To connect the steel girder web ends inside the concrete embedding, two different arrangements were considered: on one side, eight-headed stud shear connectors were welded in pairs on each face of the steel girder web, and on the other side, eight transverse bars (to replace the shear connectors) would pass through predrilled holes in the web of the steel girder end.

For each connection solution, numerical modeling as well as large-scale laboratory and onsite tests were used to develop the design approaches.

Fabrication of Connections

For all the proposed solutions, the steel components of the composite beams are first prepared in the shop and equipped with steel elements for connections (plates, holes, welded headed studs, etc.). Then, the steel girders are transported to the construction site and placed on the supports. The connection components and the reinforcement are then installed. The concrete for the slab is poured and the continuity of the composite beam is completed by placing the concrete for the connection and the transverse beam over the pier at the same time (in the case of solutions 2 and 3). With the exception of solution 1, which requires a special team for the tightening of bolts, solutions 2 and 3 do not require any skilled labor. Some preliminary calibrations were carried out, such as those needed to develop the procedure to ensure good implementation of the material between the two ends of the girder flanges in order obtain the direct contact used for connections in solutions 1 and 3, as shown in Figure 5.



(a) (b) (c)

Fig. 4. Connection solutions, slab reinforcement not shown for clarity: (a) bolted connection with direct contact; (b) butt-plate connection; and (c) embedded connection (figure courtesy of Professors Mohammed Hjiaj and Alain Lachal).

(a) (b) (c)

Fig. 5. (a) ArcelorMittal fabrication; (b) INSA fabrication; (c) implementation of direct contact (photographs courtesy of Professors Mohammed Hjiaj and Alain Lachal).

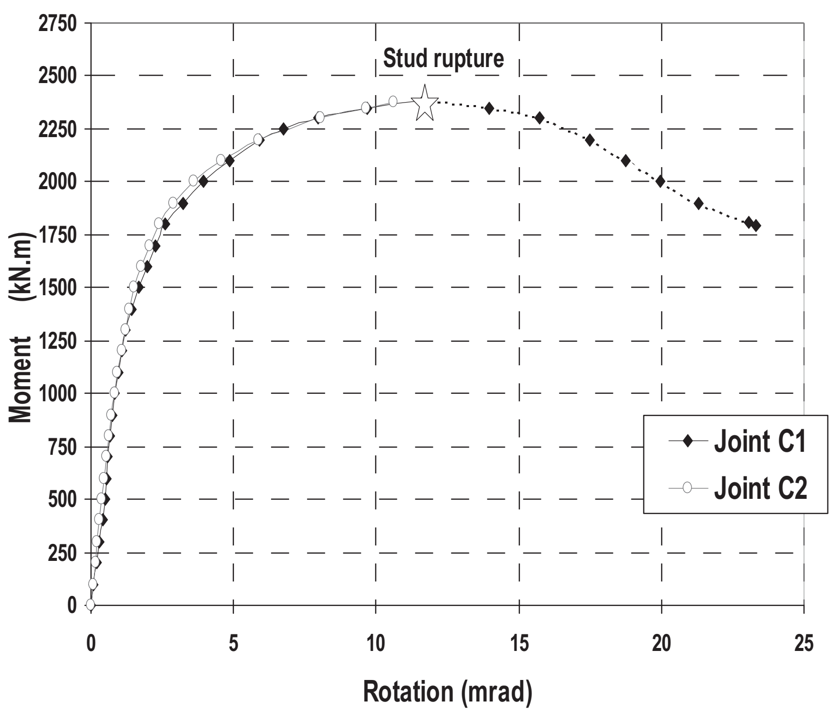
Experimental and Numerical Studies

Test specimens were designed at approximately half-scale of typical medium-span bridges. They were fabricated and tested at the Structures Laboratory of INSA–Rennes, as shown in Figure 3. The specimens were first tested under fatigue loading and then the load was monotonically increased until failure. Moment-rotation characteristics were recorded, as shown in Figure 6, as were displacements, strains and stresses.

In addition, tests on a road bridge in service were also carried out over a period of eight years, to study the in-service behavior of the connections. This is illustrated in Figure 7.

(a)

(b)



(c)

Fig. 6. (a) Connection 1; (b) connection 3; (c) moment-rotation curve for connection 3 (photographs and figure courtesy of Professors Mohammed Hjiaj and Alain Lachal).

To allow for an accurate interpretation of the test results, 2D and 3D finite element modeling was done for all of the connection types and calibrated against the experimental results. It was determined that the connections were able to achieve the continuity of the composite bridge desks with a satisfactory rotational stiffness and strength.

Connection Design

Simple design methods have been proposed for each of the three types of connections. As the basic design principle, it was decided to maintain a distribution of internal forces as close as possible to the distribution found in the beam cross-section close to the connection. This would maintain the same position of the elastic neutral axis. Because a connection is necessarily located near an intermediate support, only the negative bending moment that would be transmitted is considered. In French composite bridge design practice, the steel girder cross-sections are often slender (noncompact), such that only elastic analysis has been developed in this study.

Figure 8 provides a schematic illustration of this approach, with the normal and shear stress distributions in the composite section of the beam and the distribution of internal forces that the connection will have to transmit.

Grouped Shear Connection

A separate effort within the framework of the MIKTI project has dealt with the behavior and strength of groups of headed stud shear connectors in composite bridges. The main parameters were the material used to connect prefabricated slabs to steel flanges, the dimensions and characteristics of recesses in the prefabricated slabs, the placement of the reinforcing bars through the recesses and the number (four- or nine-headed studs per recess) and the spacing of the connectors. This is shown in Figure 9.

The interpretation of push-out test results mainly addressed the initial stiffness, the maximum strength and the ductile capacity of a group of shear connectors based on the experimental slip-shear force curves. The results have shown that the initial stiffness and the maximum strength of groups of

(a) (b)

Fig. 7. (a) Tested bridge; (b) loading of bridge (photographs courtesy of Professors Mohammed Hjiaj and Alain Lachal).

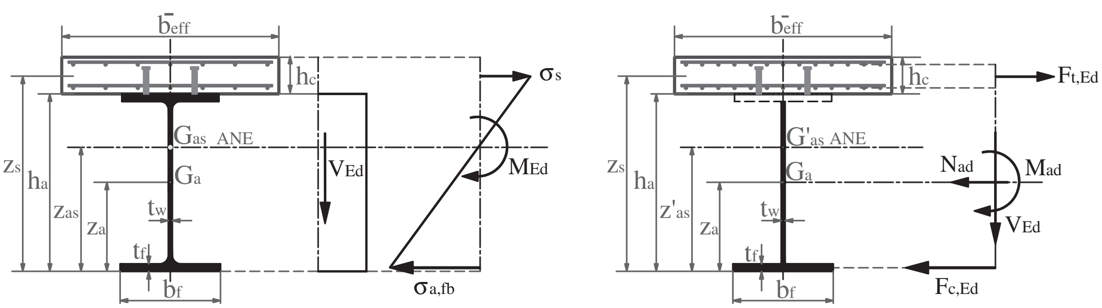


Fig. 8. Typical connection details and stress resultants (sketches courtesy of Professors Mohammed Hjiaj and Alain Lachal).

stud shear connectors increase with the performance of the concrete, whereas the slip capacity decreases.

Compared to standard test results, a reduction of about 10% of the initial stiffness and the maximum strength was observed, without a significant reduction of the slip capacity in the case of grouped stud connectors, with the same type of concrete as the concrete of the prefabricated slab.

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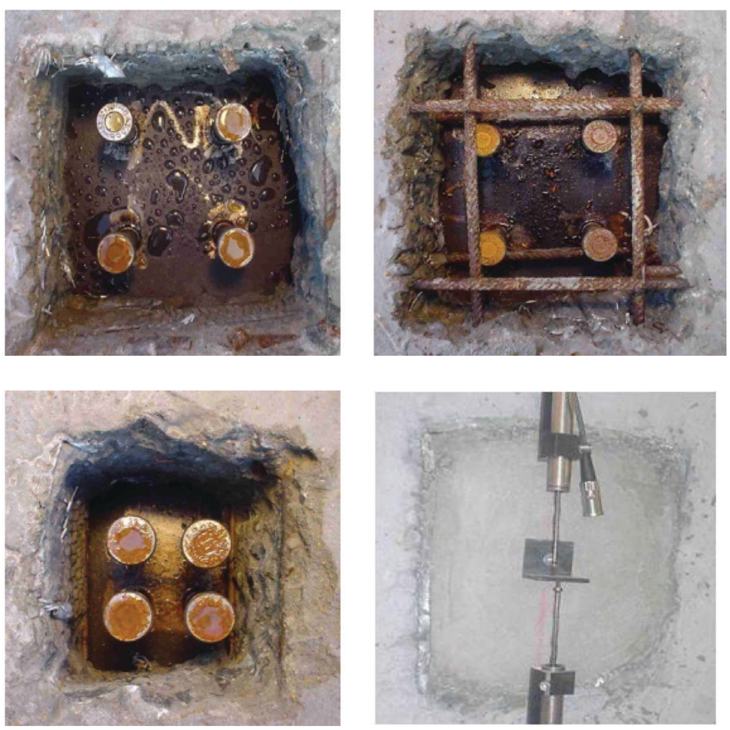

Fig. 9. Group arrangements of the stud shear connectors (photographs courtesy of Professors Mohammed Hjiaj and Alain Lachal).