DESIGNING FOR SEISMIC RESILIEN

Faster construction both before and after an earthquake

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MODERN SEISMIC DESIGN is something like the crumple zone of your car. Just like your car is designed to absorb the energy of a collision while keeping you safe inside, steel buildings are designed to absorb the energy of an earthquake while protecting building users. Unfortunately, though, a building is much more difficult to fix or replace than a car.

Forward-thinking earthquake engineers are working to change that. Where previous generations of building codes and standards have focused on life safety, emerging research and practice looks at promoting seismic resilience, allowing structures to be rapidly returned to service after a large earthquake.

Steel braced frames are a popular lateral force resisting system across Canada because they can readily be designed to provide the necessary stiffness and strength. While the diagonal braces should not visibly deform under day-to-day loading, under earthquake loading they are designed to buckle in compression and yield in tension. In this way, they can withstand the repeated cycles of earthquake energy with damage but not failure, protecting the overall integrity of the structure.

Braces are commonly made using hollow structural sections, which are connected to the beams and columns using gusset plates that are intended to bend when a brace buckles in compression. To promote desirable forms of deformation and energy dissipation during an earthquake, the braces are often connected using site-welded details, even though this adds a layer of complication to the erection process and makes post-earthquake repairs challenging. In addition, typical detailing promotes buckling out of the plane of the frame, which can cause damage to adjacent partitions or cladding.

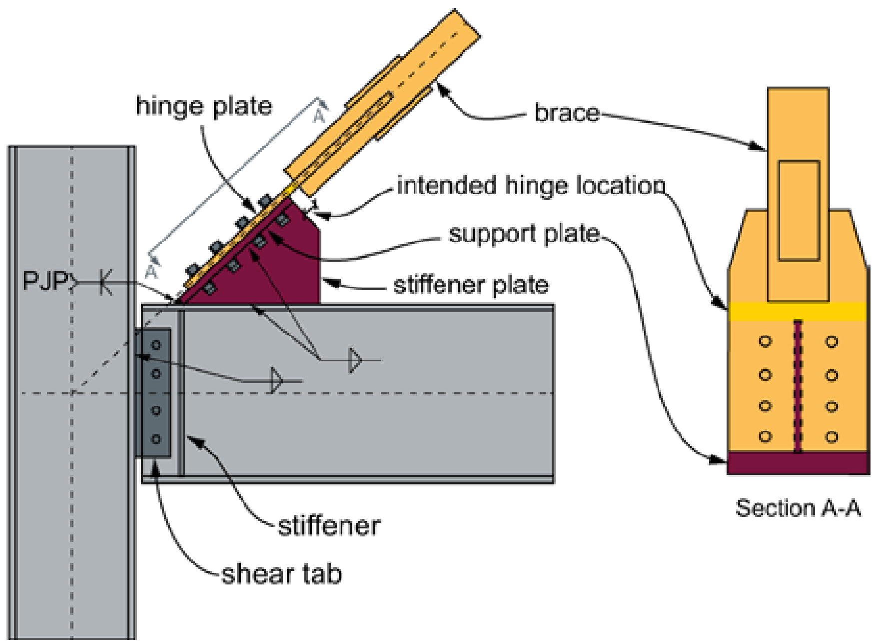

FIGURE 1: Replaceable Brace Module connection

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A NEW PARADIGM: REPLACEABLE BRACE MODULES

Since 2014 and with the support of the CISC, researchers at McMaster University have been developing an alternative approach to connecting the braces in a concentrically braced frame. This concept is based on a *Replaceable Brace Module*, a unit that is fabricated in the shop and bolted into position on site.

As shown in Figure 1, with a Replaceable Brace Module, the traditional gusset plate is replaced with a designated

CE WITH STEEL BRACED FRAMES

University; Vahid Mohsenzadeh, PhD Graduate

hinge plate that is designed to bend when the brace buckles, together with a stiffener plate to ensure stability of the assembly. In this way, the goal is to avoid site welding and out-of-plane buckling and to facilitate post-earthquake repairs.

An earlier phase of proof-of-concept testing focused on the module itself, demonstrating that the module could confine damage to within the replaceable unit while still providing the same level of seismic performance as more conventional details.

LARGE-SCALE TESTING AT MCMASTER UNIVERSITY

In this latest phase of the research, large-scale system-level testing was conducted on frames using Replaceable Brace Modules, as shown in Figure 2. This testing was possible through the support of the CISC and its members Walters Group, Salit Steel and Atlas Tube, together with the Natural Sciences and Engineering Research Council of Canada (NSERC). The purpose of these tests was to assess whether the Replaceable Brace Module was compatible with typical beam connection details, and whether the replaceable brace modules could indeed be replaced to restore the original performance of the frame even after severe seismic loading.

This 70%-scale testing represented the second floor of a multi-storey building in Vancouver. Three different beam-column connection types were included in the test program: (1) a shear tab connection (i.e. acting as "pinned"); (2) an end-plate connection (pinned); and (3) a bolted unstiffened end-plate connection (fixed). For each of these three connection types, two

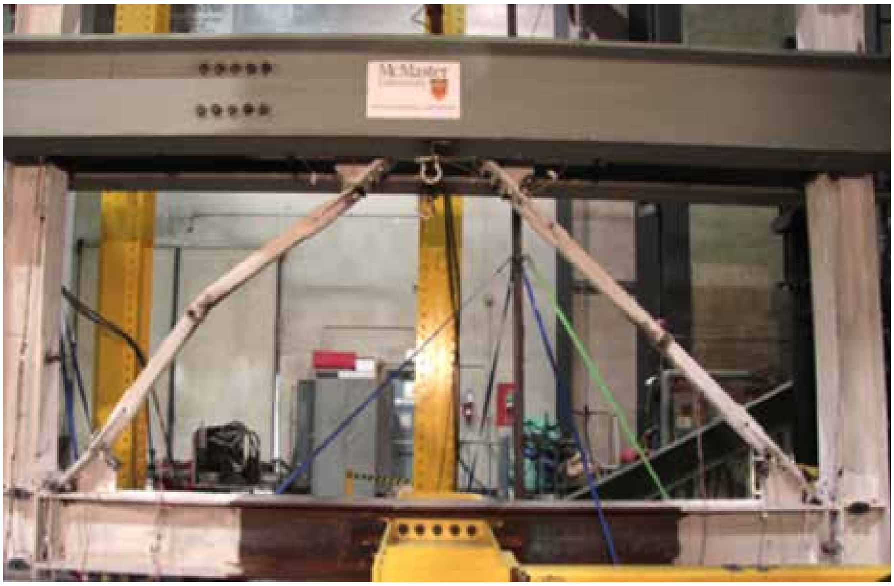

FIGURE 2: Large-scale frame testing with Replaceable Brace Modules at McMaster University

tests were conducted, one with an original Replaceable Brace Module and one with a replacement module.

Figure 3 shows typical deformations that were observed during the test program. In keeping with the design intent, damage was essentially confined to within the Replaceable Brace Modules. As intended for any brace in a seismically designed concentrically braced frame, compression buckling (Figure 3a) led to a plastic hinge and local cupping at the middle of the brace (Figure 3b), with eventual fracture in tension at that location after many large cycles of loading (Figure 3c). This eventual fracture occurred at the same point during the tests that would be expected with any well-designed brace connection detail.

As intended, the hinge plates yielded in bending (shown by the white paint flaking off in Figure 3d) to allow the brace to buckle. After a test was complete, the damaged brace module was removed and replaced relatively easily, and the frame had essentially identical performance with the replacement set of Replaceable Brace Modules.

Of the two pinned beam-column connections, the shear tab connection was preferred not only because of its ease of construction, but also because it was more effective in limiting the demands on the columns. The fixed beam-column connection saw some damage at very large drifts, but also provided the benefit of increased redundancy and reserve capacity.

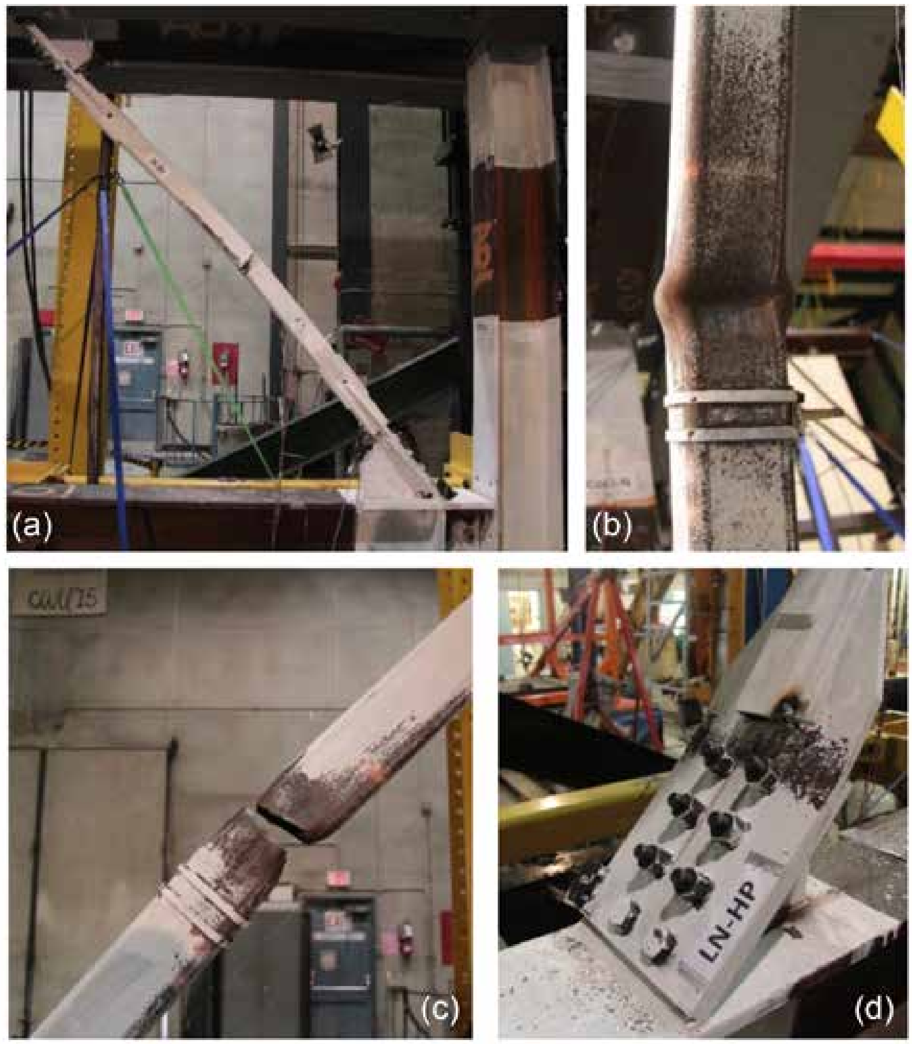

FIGURE 3: Typical Damage Progression

Overall, this test program exceeded expectations in confirming that Replaceable Brace Modules are viable within a complete seismically designed steel braced frame.

DOCUMENTATION AND DESIGN

The results of both phases of this test program have been published in two papers in the *Journal of Structural Engineering*, and the final drafts of these papers are available by contacting the author or the CISC. The design calculations for the experimental test program are also available on request, for those interested in detailed information about how a Replaceable Brace Module can be designed to achieve the benefits in construction and seismic resilience that this test program has demonstrated. AS