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Fuse performance on bracing of concentrically steel braced frames under cyclic loading

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ABSTRACT

This paper describes the development of ductile fuse system for steel angle bracings to reduce the seismic demand to the connections of concentrically braced frames. In such type of structure, the connections often need reinforcement to resist the tensile capacity of the bracing to comply with the capacity design procedure recommended by most design codes. In this research, various models of ductile fuses consisting of smoothly reduced angle section are placed on the X-bracing of a braced frame. The fuses are designed to reduce the tensile capacity of braced members to the capacity of the bolted connections. To evaluate the performance of the fuse system, two different thicknesses of single angle members with leg width of 64 mm part of an X-bracing are tested cyclically in a 1.75-m high frame representing a building story. It was observed that the braced frame with fuse could be used to reduce seismic load demand to the connections sufficiently to avoid connection strengthening that would result from the application of the capacity design principles. It was observed that properly designed fuse system in braced frame showed stable hysteretic response under cyclic loading and maintained adequate ductility with a reasonable compromise on the compressive strength of braced members. Finally, based on the study results, most efficient fuse patterns are identified for practical design applications.

1. Introduction

Concentrically braced frames are one of the most common lateral load resisting systems for steel buildings and have been studied extensively for performance evaluation under seismic loading. Results from previous research investigations [1–3] and damage to concentrically braced frame during past earthquake show that severe local buckling and premature net fracture of the brace in the connection areas significantly decrease the effectiveness of concentrically braced frame within its inelastic range of behavior. The response of concentrically braced frame in resisting seismic loads is governed by the performance of braces and connections subjected to reverse cyclic loading. To obtain the desirable performance from concentrically brace frame, the braces must fail first by showing acceptable ductility after several cycles of inelastic deformation including stretching in tension and buckling in compression. Past research [4–6] shows that concentrically braced frames can provide good seismic performance if premature fracture or tearing of the brace connection is avoided. Hence, guidelines have been produced in different codes of practice for the design of the braces and connections to give a desired capacity under seismic events. These codes [7–9] require that the connection is 'stronger' than the brace; therefore, the brace will fail before the connection. In other words, the factored resistance of the bracing connections must exceed the axial tensile strength of the bracings members, $A_gR_yF_y$, where A_g is the cross section area of the brace, F_y is the yield strength of the brace and R_yF_y is the probable yield strength of the brace accounting for variation in yield strength of actual members. In the case of brace made with angle members, unless the steel ultimate strength (F_u) is considerably larger than the yield strength (F_y), the effective net area, A_n, would have to be greater than the gross area to respect this requirement. For example, with typical values of $A_n/A_g = 0.8$ and shear lag effect to reduce connection strength by 20%, and $F_y = 300$ MPa, according to S16-09, $R_yF_y = 385$ MPa, and the required F_u would be 601 MPa for the failure to happen in the brace instead of the connection, whereas typical values of F_u that are used in design is 450 MPa. In many instances, this requirement implies the need for reinforcing the brace at the connections. The drawback of such reinforcement is that it adds significant cost and complexity to the connections.

The design of a tension–compression braced frame is usually controlled by the compressive resistance of the brace member, which is much less than the tensile resistance. The tensile resistance of brace is typically larger than what is required by calculation. The strengthening of the connection is not due to computed loads but instead to the application of the capacity design method and the actual excess of tensile

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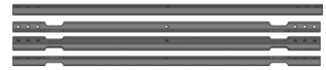
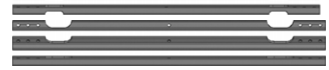
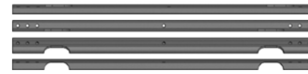
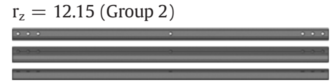
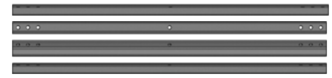
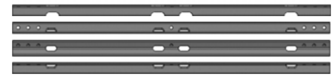
capacity in the case the member is designed for its compression capacity. Reducing the cross section of the member on sufficiently small length in order to limit reduction of compression strength would result in a reduced tensile strength and therefore limit the need for connection strengthening. The concept of incorporating a fuse in bracing to reduce tensile strength to the level strictly required by calculation is therefore interesting and has been investigated in the past [10, 11] on HSS brace. It was shown that the ductility demand with the reduced section brace was localized around the hole of the brace. This resulted in very high local material straining, but given the short brace length that this plastic straining occurred over it didn't result in a system ductility (drift of entire bracing system) that was sufficient in comparison with what was expected given the R values used in design.

In this paper, a simplified fuse system is developed for single angle members. The designed fuses are capable of reducing strength demands on connections while maintaining the load carrying capacity and adequate ductility in the braced frame system. The performance of five full cross single angle bracing with fuses is compared to the behavior of three cross angle bracings without any fuse. All X-braces are subjected to cyclic loading up to failure. Recommendations for design applications are presented based on the experimental study.

Table 1
Full-scale test specimens.

Test ID	64 × 64 × 13 A_g = 1443, r_z = 12.16 (Group 1)	Remarks
R13		Without any fuse (reference Test)
F13-1		Fuse at ends, on both legs (2 fuse system)
F13-2		Fuses at ends, on bolted leg (2 fuse system)
F13-3		Fuse at ends, on un-bolted leg (2 fuse system)
	64 × 64X × 9.5 A_g = 1110, r_z = 12.15 (Group 2)	
R9.5-1		Without any fuse (reference test)
R9.5-2		Without any fuse (reference test)
F9.5-1		Inner and outer fuses on both legs (4 fuse system)
F9.5-2		Inner and outer fuses on legs intersection (4 fuse system)

2. Experimental program

The experimental program consists of eight (8) tests on single story concentrically braced frame subjected to the effect of cyclic loading. The load is applied at the top right corner on the frame of the bracing system. The cross bracings of the braced frame are single angle members which are connected to each other at mid-point and at the ends to the frame by gusset plates assembly. Two different sizes of angle members are used in the experimental program. In each test similar sizes of angle members are used as cross bracings. In the fuse equipped tests, the fuses are placed on the angle members near the connections. The effect of designed fuses on the performance of concentrically braced frame is evaluated from the experimental study. Fig. 1 shows the dimension of test frame assembly with crossed angle members and Table 1 tabulates the test programs. The tests R13, R9.5-1 and R9.5-2 are considered as the reference tests (tests without any fuse system). In other fuse equipped tests, the locations of fuses were empirically chosen (see Table 1) with the objective to limit reduction of compression strength while achieving the goal of connection protection.

2.1. Design of specimens

Two different angles 64 × 64 × 9.5 and 64 × 64 × 13 of normal grade steel (350 W) were used for the preparation of specimens. It is observed from Fig. 1 that the length covered by the angle member in the test frame is 2657 mm (center to center of frame). The radius of gyration for the angle members about the weak principal axis, *r*, is 12.15 mm. As the two cross bracings are connected at their mid point; assuming an effective length factor, *K* of 0.5, the slenderness ratio of the bracing *KL*/*r* is109. The calculated plate slenderness ratio of angle members, *b*/*t*, where *b* is the width of leg and *t* is its thickness, were always below $145/F_y^{0.5}$ in order to comply with Canadian standard [7] for

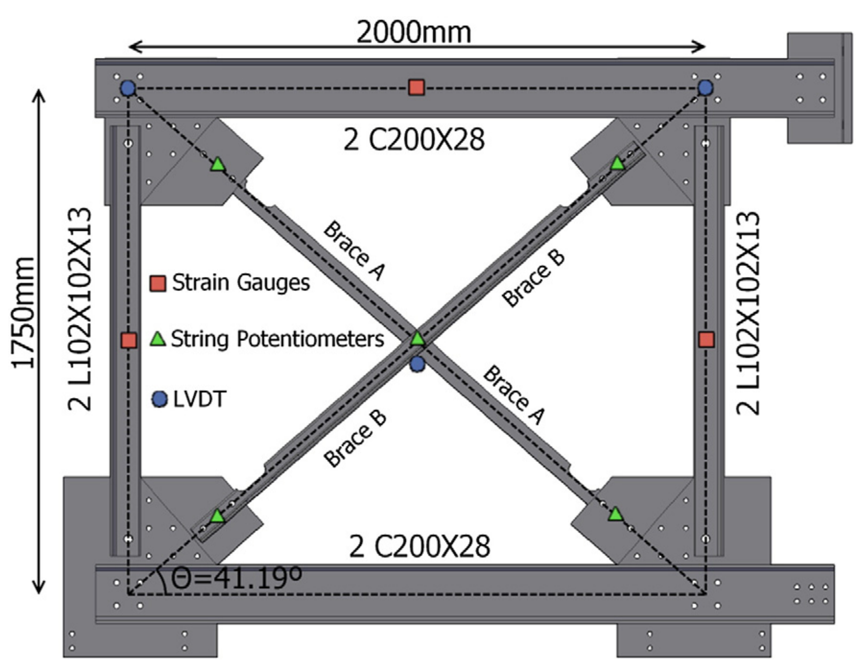


Fig. 1. Dimension of the frame with X-bracings.