

Performances of Ductile Fuses in Reducing Seismic Demand on Connections of Concentrically Steel Braced Frames

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SUMMARY:

This paper describes the development of ductile fuse system and investigates its performance to withstand seismic loading in concentrically steel braced frame. Ductile fuses are designed to reduce the tensile capacity of brace members while minimizing its compressive strength reduction. To evaluate the performance of fuse system, steel braced frames are designed as a traction/compression bracing and are constructed of single angle members connected together with a bolt at the centre and to gusset plates at ends. Two different thicknesses of angle members as cross bracing and both removable and traditional gusset plates for the end connections are considered in this study. The ductile fuses as notches are strategically placed on cross braced frames. The braced frames are then tested under reversed cyclic loading to simulate the seismic response. It was observed that the performances of braced frame were not affected significantly due to the insertion of fuses in cross bracing members. Based on test results, it was concluded that properly designed fuse system in braced frame exhibited stable hysteretic response under cyclic loading and increased the ductility significantly with a reasonable compromise on the compressive strength of braced members. Finally, based on the study some most efficient fuse patterns were identified for practical design applications.

Keywords: Ductility, Cross bracing system, Fuse design, Connection, and Seismic loading.

1. INTRODUCTION

Concentrically braced frames are one of the most common lateral load resisting systems for steel building and hence, have been studied extensively for seismic performance during an earthquake. The response of concentric braced frame in resisting seismic response is governed by the performance of braces and connections subjected to cyclic loading. To get the desirable performance from concentrically brace frame, the braces must fail first by showing acceptable ductility before the failure of any other component of the frame system. 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 (e.g. CSA S16-01, 2006, AISC, 2002) 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 bracings connections must exceed the axial tensile strength, $A_g R_y F_y$ of the bracings members, where A_g is the cross section area of the brace, F_y is the yield strength of the brace and $R_y F_y$ is the probable yield strength of the brace to account for variation in yield strength of actual members. As for the requirement for the factored strength exceeding $A_g R_y F_y$, 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 code requirement in most practical case of angle braces. This results in costly strengthening of connection. The strengthening using overly large connections are not only uneconomical but may also decrease the performance of the braces as overly large connections decrease the effective length of the brace, which may cause a decrease in ductility.

Considering that the design of a traction/compression braced frame is usually controlled by the compressive loads due to reverse seismic loading, the tensile capacity is usually higher than what is required by calculation. The strengthening of the connection is then due to an excess of capacity, not to the actual computed loads. Past research (Kahn and Hanson 1976, Foutch et al. 1987, Aslani and Goel 1989) shows that concentrically braced frames can provide good seismic performance if premature fracture or tearing of the brace and the connection is avoided. The concept of incorporating a fuse in bracing to reduce tensile strength to the level strictly required by calculation is interesting and has been investigated in the past (Kassis 2008, Rezai et al. 2000) on HSS brace. In this paper, a simplified fuse system is designed with a tensile capacity equal to the design capacity of bolted

connections. The designed fuses are capable of reducing demands on connections while maintaining the load carrying capacity and adequate ductility in the braced frame system. In the study, at first the ductility performance of designed fuse system is checked on tension members and finally, its performance is evaluated on full-scale braced system subjected to cyclic loading. Some conclusions for design applications are made based on the experimental study.

2. FUSE DESIGN

2.1 General Assumptions

The ductile fuse system is composed of strategically dimensioned notches and positioned carefully on the angle members without any kind of connection strengthening or reinforcement. The fuse system is designed to achieve the following objectives:

- reduce loads transmitted to the bolted connection assembly
- provide adequate ductility
- limit its effects on the compressive resistance of the bracings

Unlike the previous research work (Kassis 2008), the fuse is not designed to reduce capacity in tension at the compression capacity. Some preliminary work showed that a fuse used to reduce capacity in tension at the capacity in compression causes a serious reduction in cross section of the angle member. It can then develop the quick formation of plastic hinge and results an abrupt break of the system. In this study, the fuse is designed to have a capacity equal to that of the bolted connection. Thus, the fuse area, A_{fuse} , is equal to:

$$A_{fuse} = \frac{T_r}{\phi F_u} \quad (2.1)$$

In this equation, T_r is the tensile resistance of the brace connection obtained as the minimum between the effective net area fracture, bolt capacity, bearing capacity and tear-off capacity; ϕF_u is the design strength of steel. The fuse length is estimated so as a ductility of 3 is reached for the brace system with a strain in the fuse exceeding 5%. The objective of ductility of 3 is consistent with a moderately ductile system. The fuse length, L_{fuse} , is therefore:

$$L_{fuse} = \frac{\Delta_{all} - \varepsilon_y L_{brace}}{\varepsilon_f - \varepsilon_y} \quad (2.2)$$

E is the modulus of elasticity; and L_{brace} is the length of the brace.

The fuse length will then be provided on the brace. The transition zones are composed of circular cuts. If done correctly, the fuse should reach its full ductility when the connection reaches the limit computed by the designer. Thus in a properly design fuse, the rupture must be located in the fuse, not in the brace connection.

2.2 Fuse Validation Tests

To evaluate the performance of fuses on tension members; angle members (64×64×13mm) with various orientations of notches as designed in accordance with the principle presented above are considered along with the reference angle member without any notch or fuse system. A total of six specimens are used in tension test and Fig. 2.1. shows the design fuse system in tension specimens. The bracket 3 has a fuse substantially smaller than other angles due to construction restriction. All the six angles are tested in tension to evaluate their ductility potential as well as ultimate capacity to

protect the connection. Gusset plates of adequate thickness and length are used to transmit the tension in the specimens. Fig.2.2. shows the test setup for the specimens in the laboratory.

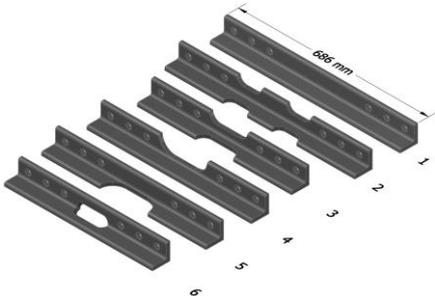


Figure 2.1. Tension test specimens for the fuse system

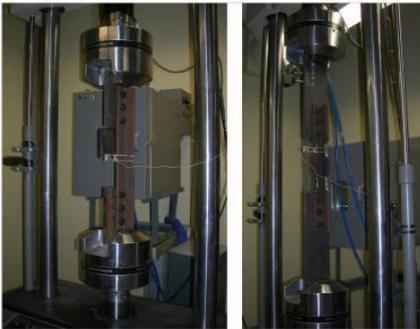


Figure 2.2. Test set up for tension specimens

The load deflection performance of the tested angle members are shown in Fig. 2.3. whereas, Table 2.1. tabulates the detail test results. The fuse strain values in Table 2.1. are obtained by matching the stress in the fuse with the stress/strain curves obtained from test sample on coupons according to ASTM-E8 protocols (ASTM 2008). It is observed from Fig. 2.3 and Table 2.1 that specimen used in test 1 did not reach its full plastic range but managed to exceed its computed connection’s capacity. The specimens used in Tests 2, 4 and 6 achieved their objectives by providing a sufficient ductility. For these specimens, the rupture occurred in the fuse (refer to Fig. 2.4.) at the design value nearly equal to the capacity of the connection. Test 3 had a smaller fuse area, but showed adequate ductility with final failure in the fuse. Test 5 did not achieve the objective and its behaviour was similar to that of angle member without any fuse system. The premature brittle failure of the connection in this test is mainly attributed to the improper orientation of the fuse.

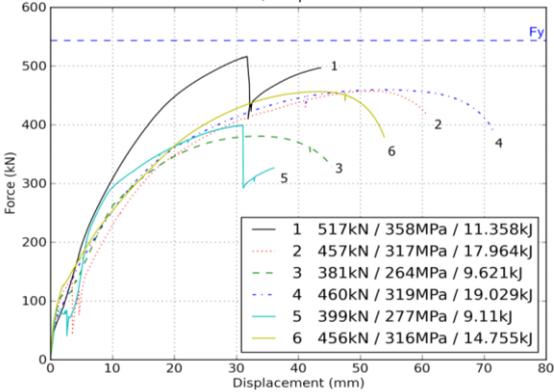


Figure 2.3. Load-displacement performance of test members

Table 2.1. Tension Test Results Of Design Fuse System In Angle Members

Test No.	F_y (MPa)	F_u (MPa)	F_u/F_y	Fuse Area (mm^2)	A_n/A_g	Maximum Force (KN)	Max. Force/Connection Capacity	Stress in Fuse/ F_y	Fuse Strain (%)
1	381	546	1.43	1443	1.00	516	1.12	0.94	0.175
2	381	546	1.43	857	0.59	457	0.99	1.40	8.85
3	373	541	1.45	721	0.50	381	0.83	1.41	8.56
4	373	541	1.45	847	0.59	460	1.00	1.45	15.7
5	373	541	1.45	847	0.59	399	0.60	1.26	3.74
6	381	546	1.43	831	0.58	456	0.99	1.47	15.7



Figure 2.4. Failure modes of tested angle members

Even though the cross-sectional area of successful fuses (for fuse 2, 4, and 6) were about 58% of the original size (fuse 1), they managed to withstand about 90% of the force that ruptured the specimen of test 1 (control specimen). As the connections remain the same in all the six tests, it is concluded that the fuse design corresponding to test 2, 4 and 6 are satisfactory to reach acceptable ductility and hence, have the potential to protect the connection failure with only a modest reduction of tensile strength.

3. FULL SCALE TESTS

The performance of angles with same notch patterns as evaluated in tension tests were used in the full scale experimentations. Two different angles 64X64X9.5 and 64X64X13 were used for the preparation of specimens. The selected angles geometrical properties and resistance were the best suited one for the test set-up.

3.1 Test Set-up

Fig. 3.1. shows the test set-up and the instrumentation used for the full-scale experimentations. A total of eight (8) full scale tests were conducted to evaluate the performances of various fuses in cross braced steel frame. The story load was applied by a 500 kN actuator on the top right section. Removable gusset plates of 6.35mm thick were used in all the tests; except one, where the traditional gusset plates were used for the end connections. The gusset plate assembly was designed to allow the out of plane rotation according to Canadian code S16-01. All connections were sand blasted to reach slip critical condition.

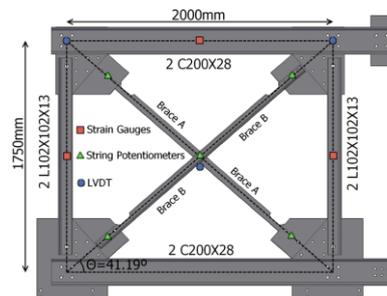


Figure 3.1. Test set-up and instrumentation

In the test set-up, the angle member from bottom right to top left was referred as the “Brace A” and the other angle was referred as “Brace B” as shown in Fig. 3.1. Strain gauges, installed on the left and right vertical double angles were used to evaluate the amount of force passing through each brace. The strain readings for the storey load were used to establish the strain response in the frame system and then from the proportion of displacement on each side, it was possible to establish the force distribution in the brace members.

3.2 Test Samples and Specimen Properties

A total of 18 angle members (nine from each of the sizes as mentioned earlier) were collected for the preparation of full scale test specimens. Member 1 and 8 were used for the tension test and the rest 16 members were used in the full scale tests. Two angle members were used in each of the test. Thus, a total of eight (8) full scale tests were carried out in the laboratory. Each test is referred according to the members used in the test (refer to Fig. 3.2.).

The length of the angle member, L , was 2657mm long (centre to centre of frame) and the radius of gyration around the weak principal axis, r , was 12.15mm. Assuming an effective length factor, K of 1.0, the slenderness ratio KL/r was 106 and the plate slenderness ration, b/t , where b is the width of leg and t is its thickness, were always bellow $145/F_y^{0.5}$ in order to comply with the article 27.5.3.2 of S16-01. Any thickness below 9.5mm would not have met this criterion. The connections were bolted with 3 3/4” A490 bolts. Threads were excluded in order to maximize the bolt capacity while minimizing the connection size. In every case, the effective net area failure governed the design. The following equation was used for the calculation of the effective net area, A_{ne} :

$$A_{ne} = A_n \left(1 - \frac{e}{L} \right) \quad (3.1)$$

where L is the connection’s length, A_n is the angle’s net area; and e is the distance from the angle’s centroid to the face of the gusset plate.

Fig. 3.2. shows eight (8) full-scale test specimens along with their mechanical properties, and calculated resistance in both traction and compression. The mechanical properties were obtained according to ASTM-E8 testing protocol (ASTM 2008). It should be noted that the calculated T_r values were always around 2.3 times higher than the corresponding C_r values. A traction only design would then be interesting; however it would not meet the requirement for slenderness ratio. The fuses in angle members were positioned to minimize their effect on the compressive resistance while performing adequately their task.

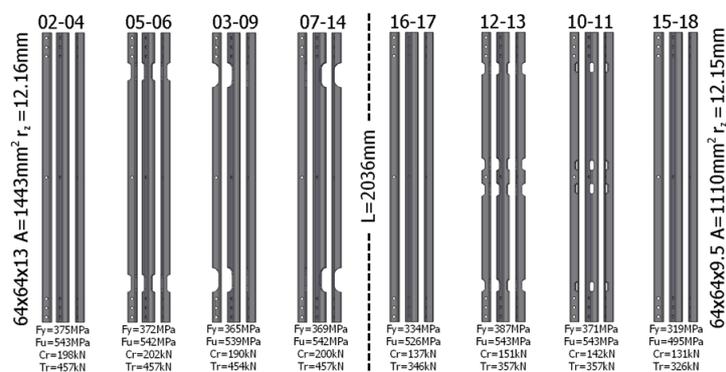


Figure 3.2. Full-scale test specimens

All tests were conducted using removable gusset plate except the test 15-18. Test 15-18 was conducted using traditional gusset plates rather than the removable ones, to make sure that the behaviour of the removable gusset plate system was similar to that one obtained with the traditional one. Tests 05-06

12-13 and 10-11 used fuse patterns ensuring a slight variation of radius of gyration. The fuse patterns used in tests 07-14 and 03-09 significantly reduce the radius of gyration and therefore the compression capacity.

3.3 Test Loading

Fig. 3.3 shows the loading protocol used for the tests. A $\pm 150\text{kN}$ test cycle was conducted at the beginning of every test to evaluate the bolt displacement in the frame and also to verify the proper behaviour of the system. The bracing was then loaded up to first buckling occurring in Brace B. This displacement is considered as the yield displacement, Δ_y , and the displacement imposed at each cycle, Δ , is based upon this yield displacement. However, this yield displacement considers the frame displacement, due to bolt displacement and slipping, that occurs during every loading. The frame displacement was about 15mm in most of the tests and therefore, the actual yield displacement was reduced by 15mm. The bracings were cycled at 2, 3, 4, 5 times the yield displacement, with consideration for the frame displacement, up to failure. Speed of loading is indicated on Fig. 3.3. Each cycle was repeated once, so two full cycles were applied to each bracing at each level of displacement.

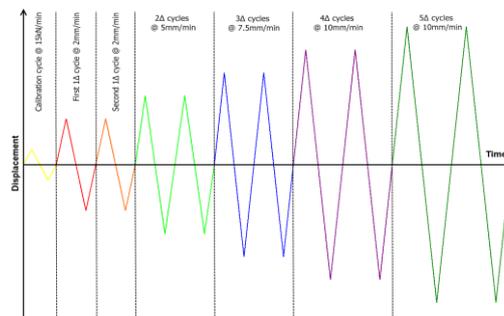


Figure 3.3. Reverse cyclic loading for full scale test

4. RESULTS AND DISCUSSION

4.1 Test Results

Table 4.1. summarizes the full scale test results under cyclic loading. It shows the cycle of failure, the failure mode, the maximum and minimum load deployed by the frame during the test and the load required by the storey to buckle chord B for the first time as obtained for all the eight tests.

The test 02-04, 16-17 and 15-18 are considered as the reference tests (tests without any fuse system). The test 15-18 was performed using traditional gusset plates instead of removable plates and received no surface treatment by using sandblasting. A comparison between the results of tests 16-17 and 15-18 indicates that the removable gusset plates have similar effect to that of traditional one on the bracing performances under cyclic loading.

The ‘rupture’ column of Table 4.1. shows the loading cycle at which the system has failed. The first term inside the parenthesis indicates the cycle and the second one indicate the displacement level. Passing the zero displacement has been placed before the parenthesis and toward the zero displacement has been placed after the parenthesis to clarify the location of failure. For example, the test 12-13 failed at the second cycle of $+3\Delta$ displacement while returning toward the zero displacement. Test 05-06 failed after crossing zero displacement at the first cycle of $+5\Delta$ displacement. As expected, the failure of all the reference tests occurred due to the failure at the connection. As compared to the reference test 02-04, the specimens with the fuse system of this group (05-06, 09-03 and 07-14) sustained more cycles but showed a modest reduction in the load carrying capacity. It is noted that the failure of test 07-14, was also due to the failure of connection. In this test, the fuse

pattern was similar to that used in test 5 of tension specimen, which also showed connection failure. Thus, it can be concluded that this pattern of fuse system should be avoided in practice in order to prevent connection failure. The other two tests (05-06 and 09-03) that are using fuse pattern 3 and 4 respectively as in tension tests, performed adequately in the full scale test. It was also observed that although in test 09-03, the fuse was able to protect the connection but its performance was relatively weak in compression. This mainly attributed to the reduction of area due to the use of relatively large fuse in that test. In the second group, the test 12-13 (fuse pattern similar to test 2 in tension) and test 10-11 (fuse pattern similar to test 6 in tension) showed satisfactory performance in full scale test as expected.

Table 4.1. Full Scale Test Results Of Frame Under Cyclic Loading

Type	Test	Rupture	Rupture Type	Fuse Area (mm ²)	Fuse r_z (mm)	Maximum Force-Stress		Story Load Min		Ist Buckling Load	
						kN	MPa	kN	MPa	kN	MPa
64X64X13	02-04	0→(1+3Δ)	Bolt shear	1443	12.16	402	278	-389	-270	400	277
	05-06	0→(1+5Δ)	Fracture	857	7.91	351	243	-330	-229	212	147
	09-03	0→(2+3Δ)	Fuse Fatigue	847	3.96	292	202	-322	-223	118	82
	07-14	0→(1+5Δ)	Connection	847	3.96	302	210	-305	-211	50	34
64X64X9.5	16-17	0→(1+5Δ)	Connection	1110	12.15	318	286	-308	-277	296	266
	12-13	(2+3Δ)→0	Fracture	673	7.72	307	276	-255	-230	307	276
	10-11	0→(1+3Δ)	Fracture	647	7.51	283	255	-262	-236	283	255
	15-18	0→(1+4Δ)	Connection	1110	12.15	306	276	-309	-279	230	207

Table 4.2. summarizes the buckling, maximum and minimum stress obtained in both braces for each of the tests conducted. The buckling strengths of braces equipped with fuses are significantly lower to those of respective reference tests (02-04, 16-17 and 15-18) when the gross area is used in calculation. The use of fuse area instead of gross area shows a better comparison of buckling strength for the tests 05-06, 10-11 and 12-13. However, the considerable discrepancy is noticed in the case of test 03-09 and 07-14, regardless of the repository used. This mainly attributed to the poor geometry of the fuses used in test 07-14 and 03-09. The same conclusions are applicable for the minimum stress.

Table 4.2. Braces Test Results

Type	Test	Stress computation	First Buckling (MPa)		Maximum stress (MPa)		Minimum stress (MPa)	
			Brace A	Brace B	Brace A	Brace B	Brace A	Brace B
64X64X13	02-04	F/A _g	-120	-129	330	298	-139	-129
	05-06	F/A _g	-65	-78	313	309	-98	-80
		F/A _{fuse}	-110	-131	527	521	-165	-135
	09-03	F/A _g	-34	-35	269	298	-48	-73
		F/A _{fuse}	-58	-60	459	507	-83	-125
	07-14	F/A _g	-34	-46	271	277	-54	-46
F/A _{fuse}		-59	-78	462	472	-92	-78	
64X64X9.5	16-17	F/A _g	-137	-129	362	364	-173	-151
	12-13	F/A _g	-53	-101	327	307	-111	-108
		F/A _{fuse}	-88	-166	539	507	-182	-179
	10-11	F/A _g	-82	-52	320	311	-87	-66
		F/A _{fuse}	-140	-89	550	533	-149	-114
	15-18	F/A _g	-139	-115	327	325	-166	-124

In the case of maximum stress, the reference test results and tests equipped with fuses show good agreement when using gross area in calculation. As the fuses were designed to yield to the ultimate load of the connection, these two results should not differ and will be the same if the fuses are designed and performed properly. The differences between the maximum values may be due to the number of cycles before failure. Specimens that have completed some test cycles are less likely to have reached their highest loads in tension. The closer agreement for the maximum stress values for

tests 05-06, 12-13 and 10-11 with the corresponding reference test values indicate that the fuses used in these tests have yielded and reached their full capacity in the plastic range.

4.2 Hysteretic Behaviour and Fuse Effectiveness

Fig. 4.1. shows the normalized hysteretic behaviour of tests 02-04, 05-06 and 03-09 (left side, for bracing with angle size 64x64x13) and tests 16-17, 12-13 and 10-11 (right side, for bracing with angle size 64x64x9.5).

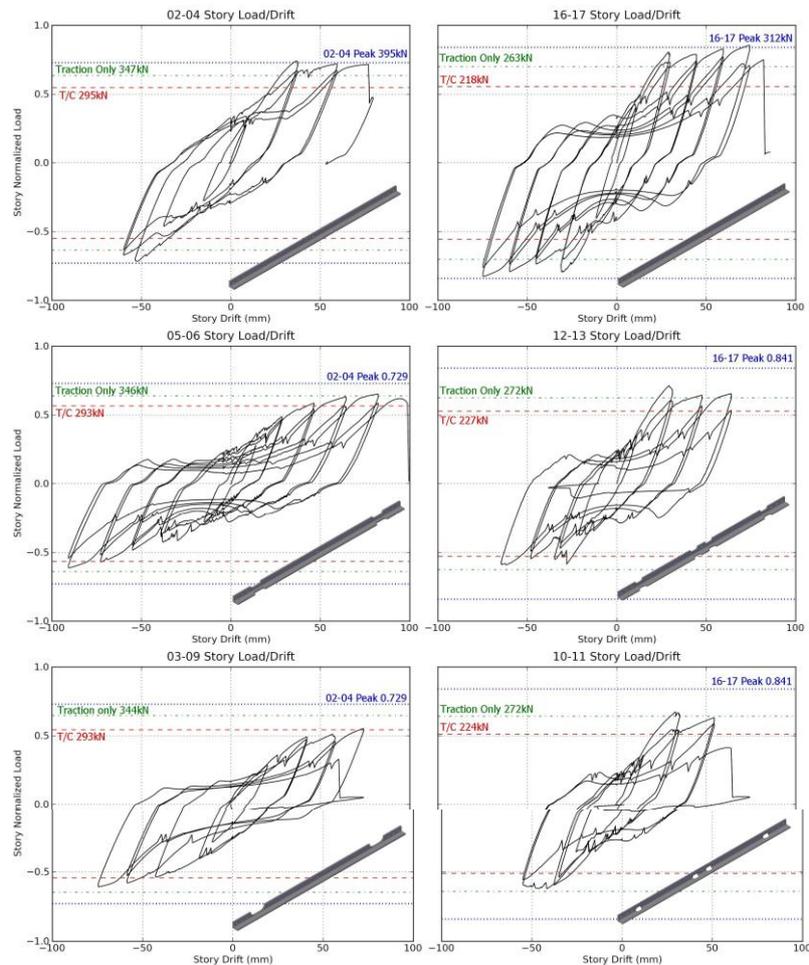


Figure 4.1. Hysteretic normalized behaviour

The normalized load value is the story load divided by the gross area of one brace and its yield stress. Results of test 15-18 are not presented because it was a calibration test similar to test 16-17 that did not provide additional information, except that the removable gusset plates did not modify the bracing system behaviour. Test 07-14 did not meet the requirement and its hysteretic behaviour is not presented. In Fig. 4.1., each graph also displays the design values for frame in traction/compression and in traction only. All graphs also show the average maximum force achieved compared to the reference test (16-17 or 02-04).

The fuse pattern used in test 05-06 were similar to those used in test 12-13, but the length was over two plastic fuses to the ends. It is observed that unlike test 10-11 and 12-13, test 05-06 and test 03-09 endured many cycles. Although, all the fuse patterns managed to meet the T/C requirement; but it took more cycle for test 05-06 and 03-09, unlike test 12-13 and 10-11 which met it during the first cycle. Furthermore, test 05-06 also reached the traction only requirement.

5. CONCLUSIONS AND RECOMMENDATIONS

In this paper, the experimental performance of various fuses in the cross bracing of steel frames were evaluated. The designed fuses have tensile capacity equal to the capacity of bolted connections. The ductility potentials of various fuses were evaluated using small scale tension tests. It is concluded that properly designed and strategically placed fuses has increased the ductility of the member to a satisfactory level and in all such tension tests the failure occurred by the yielding of the fuses. The poor geometry and improper placement of fuses significantly affect the performance of the fuse in achieving the objective to protect the connection's failure.

The results obtained during small scale tests were also observed in full-scale tests. In most designs, the fuse managed to lower the load passing through the connection to its computed resistance while providing a full ductile behaviour. The full scale tests also exposed the performance of various fuse designs, fuses positions and distributions. Braces equipped with long fuses placed at both ends of the brace (05-06) met the traction criteria and endured as many cycles as the reference test. These braces also demonstrated constant strain hardening during the loading but showed a significant loss in compression capacity.

Braces equipped with short fuses placed at 4 places (12-13 and 10-11), did not lose as much compression resistance, but reached their ultimate loads sooner in the test loading and then failed accordingly. This behaviour could be attributed to the shorter fuse that developed excessive curvature more easily and/or to the 4 fuses distribution that could have created a severe imbalance between the two brace during the loadings. Even though the braces equipped with fuses lost a certain amount of strength compared to the reference tests, they all met the requirement of a traction/compression design. The load redistribution between the two braces managed to meet the requirement set by the traction/compression design which was based upon a 50-50 load distribution.

In general, the fuse pattern used for tests 05-06, 12-13 and 10-11 were the most efficient, unlike test 03-09 and especially test 07-14 which behave poorly mainly because of their inadequate fuse geometry.

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