Experimental Study of Bolted Connection Strength at Elevated Temperatures

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ASTM A325 and A490 bolts are widely used on bolted connections in steel structures (ASTM A325-04, A490-04). Bolted connections are designed based upon their strength at ambient temperature; however, their strength at elevated temperatures is crucial to the performance of a structure during a fire. Understanding their behavior at elevated temperature is one of the keys to evaluate the fire resistance capability and fire safety of steel structures. In the Cardington series of fire tests, both fire protected and unprotected bolted beam-column connections failures were observed but not investigated thoroughly (Cardington Fire Test Report, 1998). Some research work has been focused on the stiffness variation of bolt connections at elevated temperatures. Theoretical models and FE simulations have been carried out (Liu, 1996; Silva et al., 2001; Al-Jabri, 2004). Little experimental work has been done to investigate the ultimate capacity of bolt connections at elevated temperature.

A research program was started in 2002 to study the ultimate capacity of bolted connections at elevated temperatures by the authors, which included large amounts of experimental work on both the bolts and the connections. As part of this study, the stiffness and shear strength of A325 and A490 bolts with temperature was investigated (Yu and Frank, 2009). The results of the connection tests which investigated the bearing and block shear capacity limit states are presented in this paper. Residual slip load capacity of fully tightened A490 bolt connection after exposure to different elevated temperatures was also presented.

TEST SETUP AND SPECIMEN DESIGN

Single-Bolt Connection

The single-bolt connection was designed to study the bearing capacity of steel plate at elevated temperature. Figure 1 shows the dimensions of the connection plates. The connection was made with two pieces of ⅜-in.-thick ASTM A572 Grade 50 steel plates and one ⅞-in.-diameter, 3-in.-long A325 bolt. The ASTM A572 Grade 50 steel had measured dynamic yield strength of 57.1 ksi and dynamic ultimate tensile strength of 78.6 ksi at ambient temperature. ("Dynamic" means the cross head of the test machine moved continuously at a constant speed without any pause.) The bolt was installed by hand to compact the connection and lightly tightened to minimize the clamping force and friction force that could be generated between the connected plates. An ASTM F436 washer was installed under the ASTM A563 Grade DH nut. The 1⁹⁄₁₆-in. holes in both the top and bottom plates were used to connect the test connection to the loading clevises with a pin and were designed not to fail. The ¹⁵⁄₁₆-in. bolt hole in the bottom plate was designed to have bearing failure at ambient temperature. Two end distances, ⅞ in. and 1⁵⁄₁₆ in., were tested in the temperature range up to 800 °C (1472 °F). These two end distances, named as 1.0*d* and 1.5*d*, corresponded to the edge distances of 1.0 and 1.5 times the nominal diameter of the A325 bolt.

Figure 2 shows the single-bolt connection test setup. The test system consists of an electric furnace, two stainless steel loading clevises, load frame, hydraulic ram, and data acquisition equipment. The furnace has a heating capacity of 800 °C (1472 °F). Figure 3 shows the heating time temperature curve of the furnace with ASTM standard fire heating curve (ASTM, E119-00a). The average heating rate is about 3.6 °F/min (2.0 °C/min). Because the strength of low carbon steels is insensitive to the time exposed to elevated

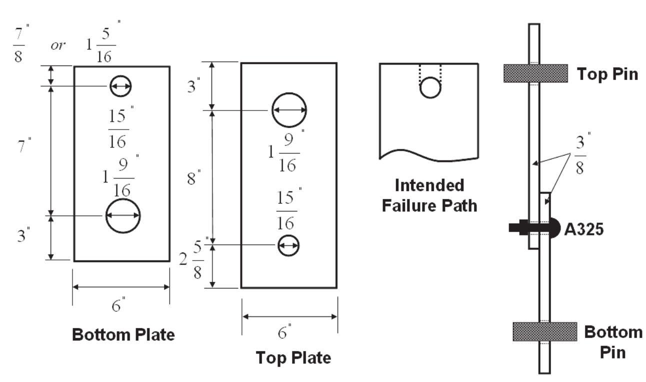

Fig. 1. Design of single-bolt connection (1 in. = 25.4 mm).

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temperatures, it is believed that the test results presented here are comparable to other similar tests performed at different heating rates. Two Type K thermocouple wires are inserted between connection plates to monitor the specimen temperature during test. The resolution of temperature readings is ±0.1 °C (0.18 °F). Furnace temperature is set to maintain specimen temperature at the desired level. Machine vision technology similar to that used by Spyrou and Davison was adapted to measure connection deformation, which is defined as the relative movement of connection plates (Spyrou and Davison, 2001). Figure 4 shows the visual targets—two pair of punch marks orthogonally oriented—and the connection deformation under load. The load is measured by a 200-kip load cell with ±0.1% accuracy.

Twenty-one single bolt connections were tested at temperatures from ambient temperature to 800 °C (1472 °F). All the tests were constant temperature tests and loaded quasi-statically. The connection was installed in the furnace at ambient temperature and heated to the desired temperature level before loading started. Once the desired specimen temperature was reached and the specimen had reached thermal equilibrium, the temperature in the furnace was kept constant. The axial tension load was then applied gradually until failure occurred.

Two-Bolt Connection

Two-bolt connections were designed to investigate block shear capacity at elevated temperature, as shown in Figure 5. The connection was made with three pieces of ½-in.-thick ASTM A572 Grade 50 steel plates and two ⅞-in.-diameter, 3-in.-long A490 bolts. The Grade 50 steel had measured dynamic yield strength of 56.3 ksi and dynamic ultimate strength of 73.0 ksi at ambient temperature. The 1⁹⁄₁₆-in. holes were used to connect the specimen to the stainless loading clevises. The 3-in.-long A490 bolts were cut and rethreaded from 7-in.-long A490 bolts from the same manufactured lot that had been tested for shear capacity at elevated temperatures (Yu and Frank, 2009). ASTM F436 washer and ASTM A563 Grade DH nut were used. All the bolts were snug tightened. The higher strength A490 bolts were used in these specimens to produce a block shear failure rather than a bolt shear failure.

The loading test set up was the same as the single-bolt connection test shown in Figure 2. Ten connections were tested. Seven of them were constant temperature tests and the other three were tests under constant load. The constant temperature test procedure on two-bolt connections was the same as that of the single-bolt connection tests. In constant load test, the tension load in specimen connection was maintained while the furnace temperature was increased slowly until failure occurred. Specimen temperature, load and deformation are all recorded during the test.

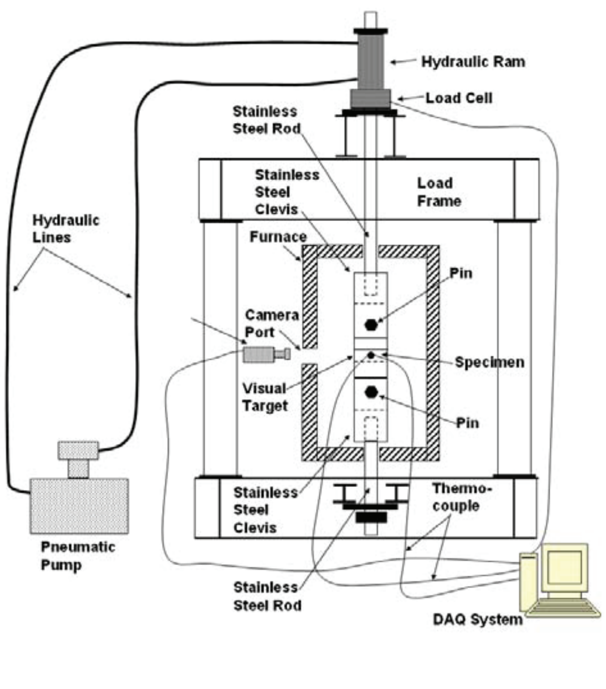


Fig. 2. Single-bolt connection test setup.

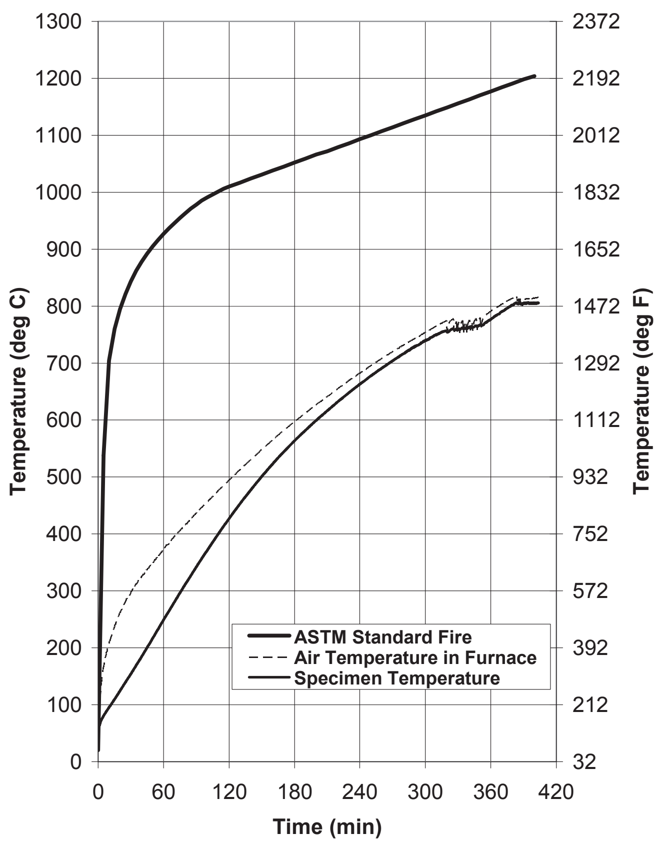


Fig. 3. Heating time temperature curve of the electric furnace.

Slip Load Test

A standard test method for determining the slip load of bolted connection is defined in the RCSC *Specification for Structural Joints Using ASTM A325 or A490 Bolts* (Appendix A, AISC 2005). The specimens used for the slip load test had the same geometry as the standard compression test specimen given by AISC. The clamping force was provided by a tension control A490 bolt. The pretension force in the A490 bolt used in the specimens was determined by tightening the A490 bolt on a Skidmore load cell. The average of three results was used as the estimated initial clamping force in all the specimens. The steel plates were sand blasted on both surfaces to produce surfaces with uniform slip coefficients on each plate.

The specimens were bolted together at ambient temperature. Nine connections were made in each batch and three were randomly picked as control samples which were not heated. The other six specimens were heated to desired temperature levels in the furnace and cooled outside of the furnace. After the connections temperature reach ambient temperature, they were tested to determine their slip loads.

TEST RESULTS

Single-Bolt Connection

Figure 6 shows the failure mode and failure paths of the single-bolt connections with 1.0*d* end distance. The tests are labeled using the first letter of their title followed by the test temperature. For example, the label SC-T300-D10 refers to *s*ingle-bolt *c*onnection at a *t*emperature of *300* degrees Celsius with an end distance *D* of *1.0* times the nominal diameter of the bolt. Specimens failed in bearing at all the temperatures except 700 °C (1292 °F). As test temperature increased from ambient temperature to 500 °C (932 °F), the bearing failure paths changed from parallel to flared fracture path. At 600 °C (1112 °F), bearing capacity was very close to the shear capacity of bolt. The bolt had under gone considerable shear deformations as shown in the Figure 6(g). At 700 °C (1292 °F), the connection failed by bolt shear with significant bearing deformations around the bolt hole. At 800 °C (1472 °F), a bearing failure occurred with very little shearing deformation on the bolt shank.

Figure 7 shows the load deformation curves of 1.0*d* single-bolt connections at elevated temperatures. From ambient temperature to 300 °C (572 °F), the load capacity of the single-bolt connections increases with temperature while deformation capacity decreases. From 300 °C (572 °F) to 500 °C (932 °F), load capacities of the connections begin to drop and deformation capacities of the connection are less than those at ambient temperature. From 600 °C (1112 °F) to 800 °C (1472 °F), load capacity drops significantly and the deformation capacity increases.

Figure 8 shows the failure mode and failure paths of the single-bolt connections with 1.5*d* end distance. From ambient temperature to 300 °C (572 °F), the 1.5*d* connection failures were similar to connection with a 1.0*d* end distance. Between 300 °C (572 °F) and 400 °C (752 °F), the failure mode changed from bearing failure to a shear failure of the bolt. The amount of bearing deformation at the bolt hole after the test indicates the shear capacity of bolt is close to bearing capacity of plate at 400 °C (752 °F) and 800 °C (1472 °F). At 500 °C (932 °F), 600 °C (1112 °F) and 700 °C (1292 °F), the amount of bearing deformation is very small, indicating the bearing capacity of the bolt hole is much higher than shear capacity of the bolt.

Figure 9 shows the load deformations curves of single-bolt 1.5*d* connections at elevated temperatures. Connection stiffness drops slightly at 100 °C (212 °F), compared with that at ambient temperature. Connection stiffness then increases at 200 °C (392 °F) and goes back down at 300 °C (572 °F). Due to the failure mode change from bearing failure to bolt shear

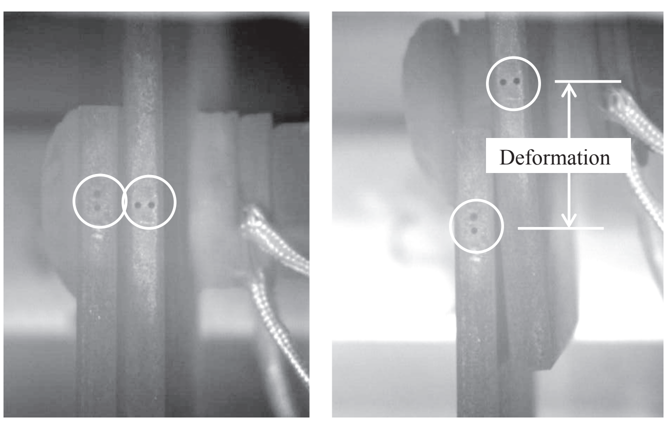


Fig. 4. Visual targets on single-bolt connection plates and connection deformation.

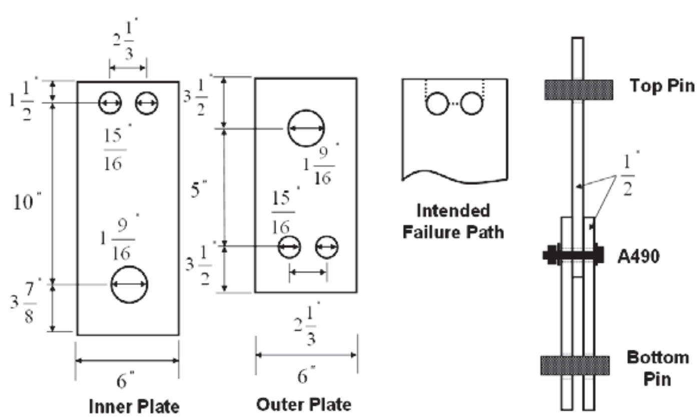
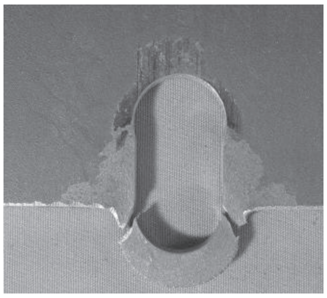
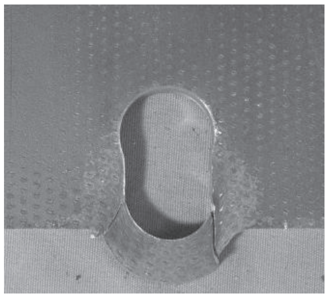


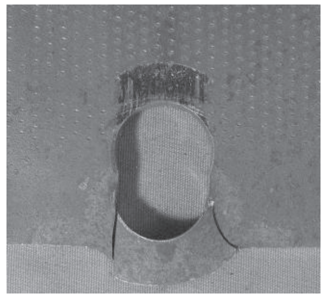
Fig. 5. Design of two-bolt connection (1 in. = 25.4 mm).



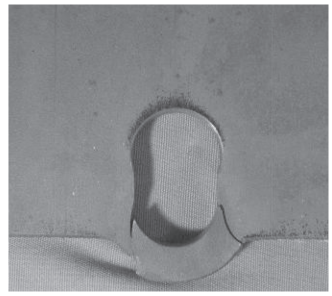
(a) SC-T25-D10
(25 °C, 77 °F)



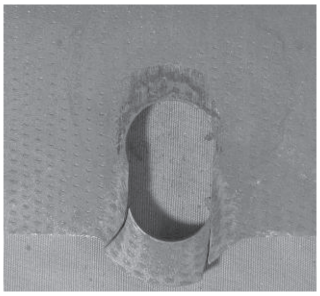
(b) SC-T100-D10
(100 °C, 212 °F)



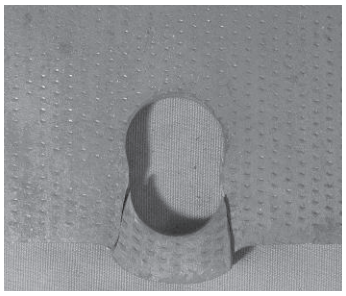
(c) SC-T200-D10
(200 °C, 392 °F)



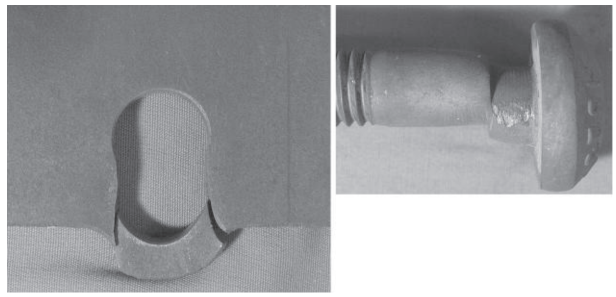
(d) SC-T300-D10
(300 °C, 572 °F)



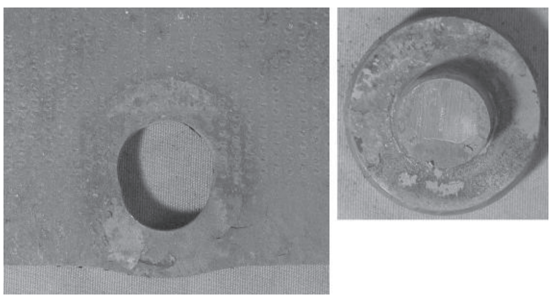
(e) SC-T400-D10
(400 °C, 752 °F)



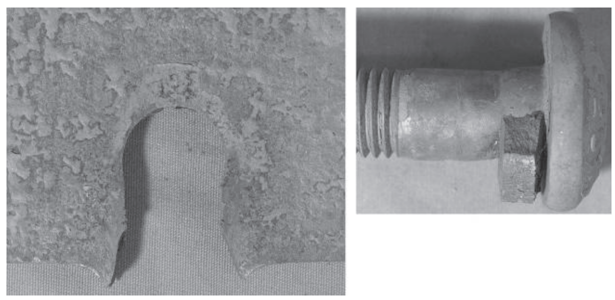
(f) SC-T500-D10
(500 °C, 932 °F)



(g) SC-T600-D10 and half-sheared bolt (600 °C, 1112 °F)



(h) SC-T700-D10 and sheared bolt section (700 °C, 1292 °F)



(i) SC-T800-D10 and intact bolt after test (800 °C, 1472 °F)

Fig. 6. Single-bolt connections ($L_e = 1.0d$*) failures at different temperatures.*

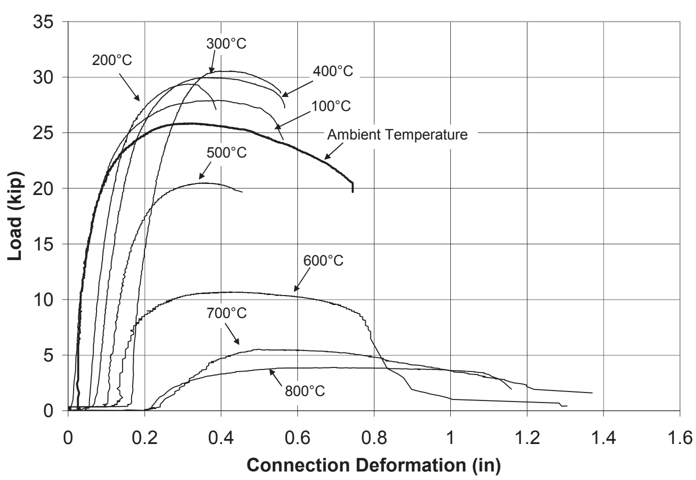
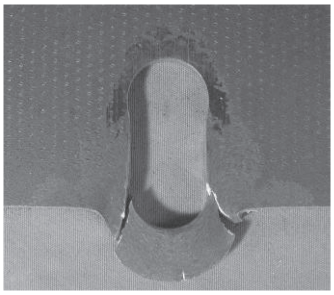
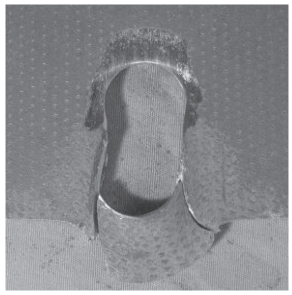


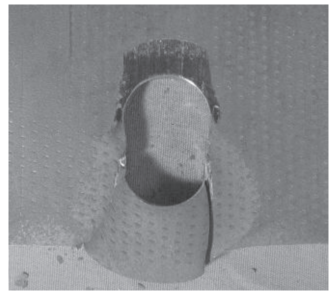
Fig. 7. Load deformation curves of single-bolt $L_e = 1.0d$ *connection at elevated temperatures (1 kip = 4.448 kN).*



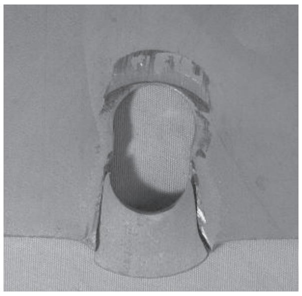
(a) SC-T25-D15
(25 °C, 77 °F)



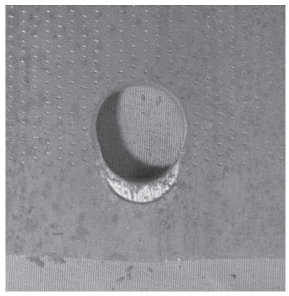
(b) SC-T100-D15
(100 °C, 212 °F)



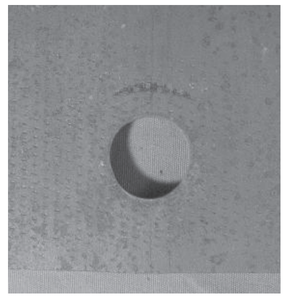
(c) SC-T200-D15
(200 °C, 392 °F)



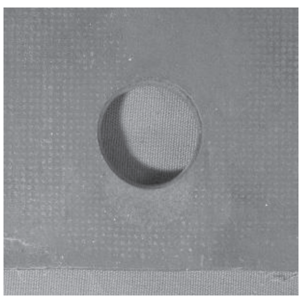
(d) SC-T300-D15
(300 °C, 572 °F)



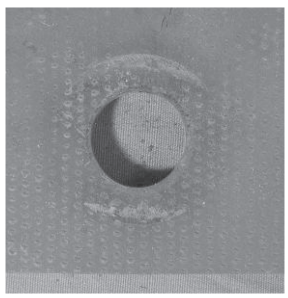
(e) SC-T400-D15
(400 °C, 752 °F)



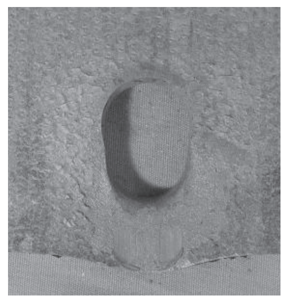
(f) SC-T500-D15
(500 °C, 932 °F)



(g) SC-T600-D15-1
(600 °C, 1112 °F)



(h) SC-T700-D15
(700 °C, 1292 °F)



(i) SC-T800-D15
(800 °C, 1472 °F)

Fig. 8. Single-bolt connections ($L_e = 1.5d$*) failures at different temperatures.*

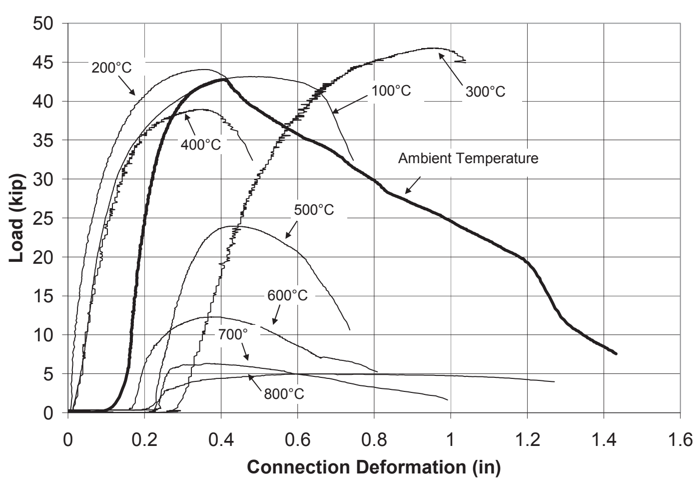


Fig. 9. Load deformation curve of single-bolt $L_e = 1.5d$ *connection at elevated temperatures (1 kip = 4.448 kN).*

failure at 400 °C (752 °F), the connection stiffness at 400 °C (752 °F), 500 °C (932 °F) and 600 °C (1112 °F) are higher than the stiffness at 300 °C (572 °F). The deformation capacity of tested connections increased due to the increased ductility of the bolts from 500 °C (932 °F) to 700 °C (1292 °F). The very large deformation capacity at 800 °C (1472 °F) was the combination of bolt ductility and bearing deformation on the plate.

Figure 10 is a plot of the load capacities of the connections at different temperature levels. From ambient temperature to 300 °C (572 °F), the capacities of the single-bolt connections with 1.0*d* and 1.5*d* end distances increase with the temperature by approximately 5 kips, a 15 to 20% increase. The capacity of 1.0*d* connection drops slightly by about 2%—from 300 °C (572 °F) to 400 °C (752 °F). However, the capacity of 1.5*d* connection drops significantly as the failure mode changed from bearing failure of the steel plate to the shear failure of A325 bolt. From 400 °C (752 °F) to 800 °C (1472 °F), the capacity of 1.5*d* connection is controlled by the shear capacity of the A325 bolt. In the same temperature range, bearing failure is still the controlling failure mode in 1.0*d* connection except at 700 °C (1292 °F). The shear capacity of the ⅞-in. A325 bolt is close to the bearing capacity 1.0*d* connection from 600 °C (1112 °F) to 800 °C (1472 °F). The structural steels and high-strength bolts have different strength reduction rates with temperature. The high-strength bolt is quenched and tempered while the structural steel is hot rolled. The bolt loses its strength rapidly above 300 °C (572 °F) when the test temperature exceeds the tempering temperature of the bolt (Honeycombe, 1981; DeGarmo, 1979; Kirby, 1995; Yu and Frank, 2009). In Appendix 4 of the AISC *Specification*, structural steel is assumed to have no reduction in strength until it temperature exceeds 400 °C (752 °F) (AISC, 2005).

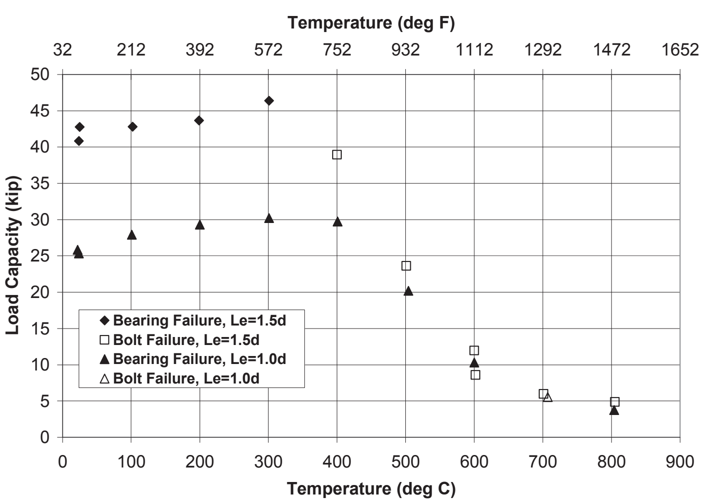


Fig. 10. Load capacities of single-bolt connections at elevated temperatures (1 kip = 4.448 kN).

Two-Bolt Connections

Figure 11 shows the results of the two-bolt connections tested at constant temperatures from 300 °C (572 °F) to 800 °C (1472 °F). The room temperature test was conducted as part of a companion study at the laboratory (Brown et al., 2007). At 300 °C (572 °F), the test connection has almost the same capacity as it does at ambient temperature. From 400 °C (752 °F) to 700 °C (1292 °F), the connection capacity almost drops linearly with its temperature, from 104 kips to 21 kips. The rate of decrease in connection capacity is less from 700 °C (1292 °F) to 800 °C (1472 °F). There is only an 8-kip-decrease in capacity at these high temperatures. It is also noticed that there is no increase in strength at 300 °C (572 °F) and 400 °C (752 °F), which was found in the bearing tests. Figure 12 shows the load deformation curves for the two-bolt connections in the constant temperature tests. As temperature increases, connection stiffness decreases and ductility increases.

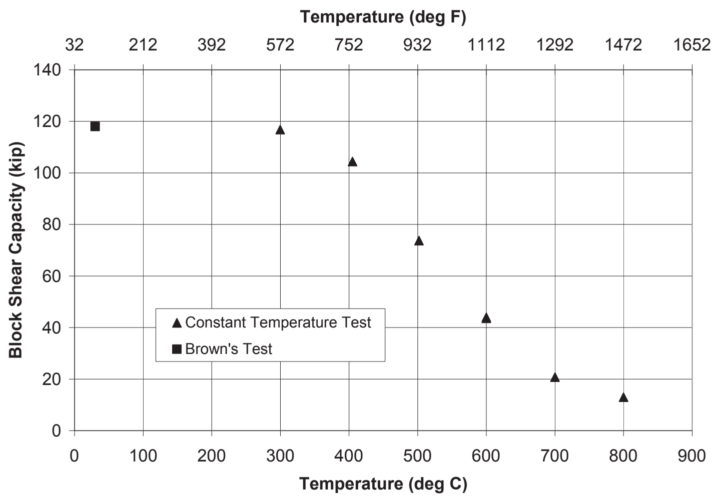


Fig. 11. Two-bolt connection constant temperature test results (1 kip = 4.448 kN).

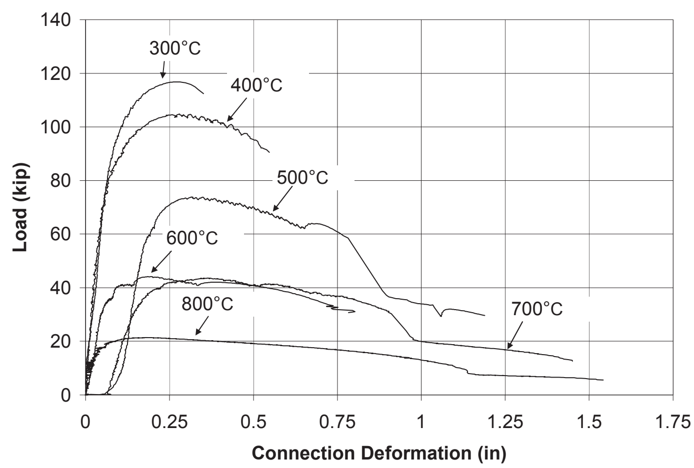
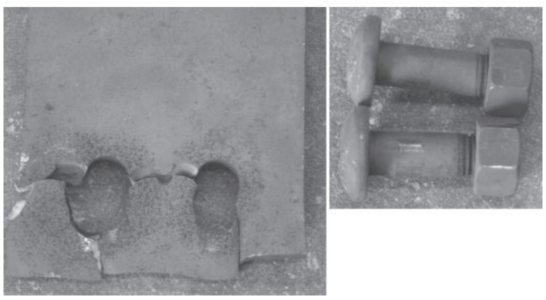


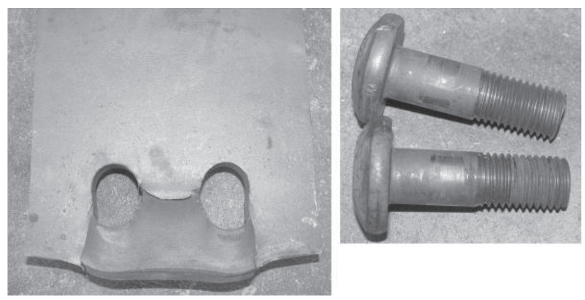
Fig. 12. Load deformation curves of two-bolt connection constant temperature tests (1 kip = 4.448 kN).

Figure 13 shows the block shear failures and the condition of the bolts after the tests. At 300 °C (572 °F), the ASTM A572 Grade 50 structural steel is in the blue brittle range (where the ductility of steel drops significantly) and an unusual half net section fracture-block shear failure occurred. At 400 °C (752 °F), normal block shear failure occurs. Right after the middle tensile part fractures, shear failure occurs on both shear paths. From 500 °C (932 °F) to 800 °C (1472 °F), the block failure can be divided into two phases: tensile failure first and then shear failure. The gap between the failed ends of tensile part indicated the connection still carries load by shear after the tensile ligament between the holes fractured. After a large amount of shear deformation, the material included in block shear fails in tension at two tips. At temperatures lower than 500 °C (932 °F), the A490 bolts has no significant deformation, which indicates the A490 bolt's shear capacity is much higher than block shear capacity of the plate. However from 600 °C (1112 °F) to 800 °C (1472 °F), larger deformations are found on the bolt shank, which indicates the difference between bolt shear capacity and block shear capacity of plate is small.

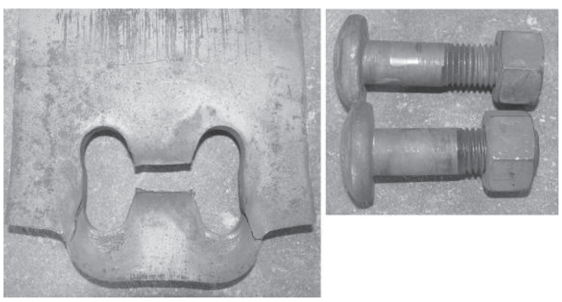
Constant load tests were performed to simulate the behavior of bolted connections in a fire event. Figure 14 shows the time-temperature and time-deformation curves of constant load tests. Three load levels, 33 kips, 60 kips and 75 kips, are tested. All the connections show very small deformation increase until its temperature reaches a critical level. The connection deformation then starts to increase quickly, and connection failure occurs a few seconds later. The failure temperature was taken as the temperature when the connection ceases to carry the load. Due to the limitations of the electric furnace, the connections are exposed to high



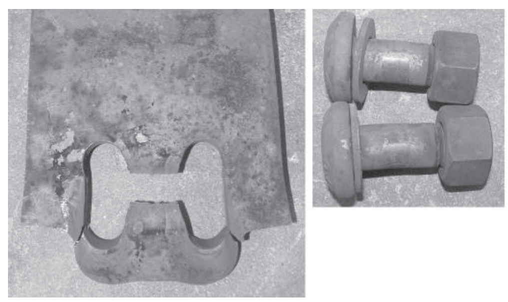
(a) TC-T300-CT (300 °C, 572 °F)



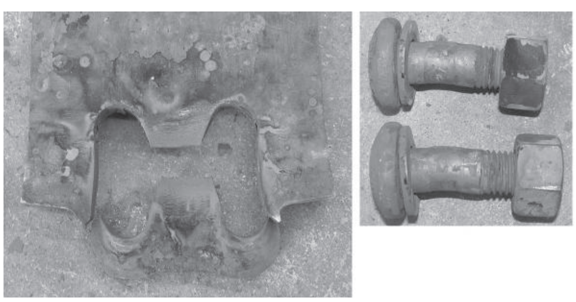
(b) TC-T400-CT (400 °C, 752 °F)



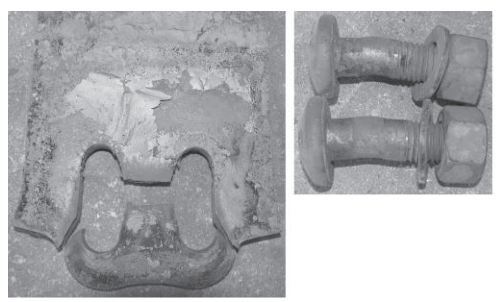
(c) TC-T500-CT (500 °C, 932 °F)



(d) TC-T600-CT (600 °C, 1112 °F)



(e) TC-T700-CT (700 °C, 1292 °F)



(f) TC-T800-CT (800 °C, 1472 °F)

Fig. 13. Block shear failures at different temperature levels (constant temperature tests).

Table 1. Tension Force in A490 Bolt after Shearing of Spline				
Bolt No.	Bolt 1	Bolt 2	Bolt 3	Average
Tension force (kips)	57.0	58.0	57.0	57.3

temperature for a longer time—more than 2 to more than 3 hours—than they would experience in the ASTM standard fire test or in an actual fire with the connection unprotected. The time at a particular temperature would be less in the ASTM test than in these tests. No significant deformation occurred in these sustained load tests until the connection was within 50 °C (90 °F) of the failure temperature. Any creep effects would be less in the ASTM standard fire test protocol due to its rapid temperature increase relative to these tests.

Figure 15 shows the constant temperature test results plotted with the constant load test results. The two types of tests produced the same strengths. Therefore, it appears that the test results are not influenced by the heating and loading path taken during the tests. The effect of the load sustained at lower temperatures did not significantly influence the strength or deformation of the connection. Based upon these results, it is apparent the constant temperature test results can be used to estimate the behavior of bolted connections regardless of the time-temperature history the connection experiences during a fire event.

Slip Load of Fully Tightened A490 Bolt Connection

The pretension force in tension control A490 bolts used in the test specimens was measured with a Skidmore load cell. The test results are shown in Table 1.

Three batches of connections were tested. Before making a connection, all the steel plates were blasted using a fine sand blasting medium to provide a uniform surface to minimize the variance among connections within the batch. The preparation was not intended to duplicate the surface roughness of a commercially blasted surface. In each batch, three connections were randomly picked as the control samples and were tested without being heated. The loss of slip resistance was determined by comparing the control test results to the results of the heated connections. Among the nine control connections, seven results were between 30 kips and 40 kips. The test results show a good consistency across test batches with two exceptions: a low load of 26.6 kips and a high load of 54.0 kips. The average slip load of each batch of the control tests, neglecting the two outliers, was between 31.4 to 33.3 kips. These slip loads correspond to a slip coefficient of 0.27 to 0.29, using the average bolt tension determined in the Skidmore load cell.

Figure 16 gives the absolute slip loads of the heated connections tested after cooled to ambient temperature. From ambient temperature to 400 °C (752 °F), the slip load increased from about 35 kips to 50 kips. Therefore, slip connections maintain their slip capacity after being exposed to a temperature lower than 400 °C (752 °F). However, the slip capacity dropped significantly from 400 °C (752 °F) to 800 °C (1472 °F).

The reason for a slip resistance increase from ambient temperature to 400 °C (752 °F) might be due to the increase in the surface roughness due to oxidization and the bolt tension evidently remaining constant. During the heating and cooling phases, the connection underwent expansion and shrinkage. That might have resulted in a better contact between the surfaces. The rapid drop above 400 °C (752 °F) is probably due to a loss of bolt tension. From the shear tests

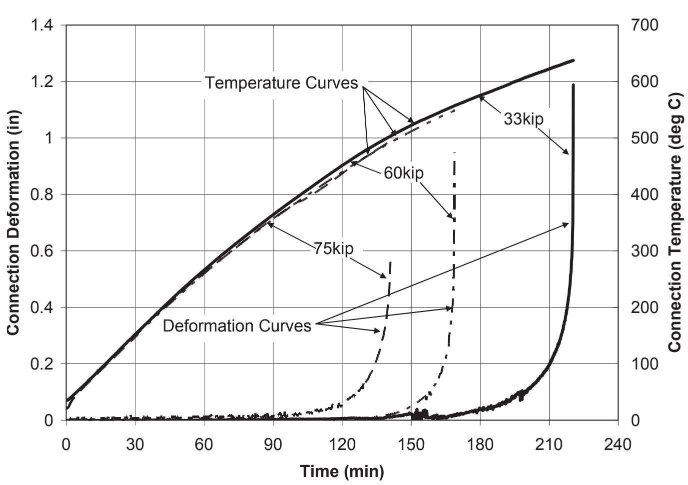


Fig. 14. Time-deformation and time-temperature curves of constant load tests (1 in. = 25.4 mm, 1 kip = 4.448 kN).

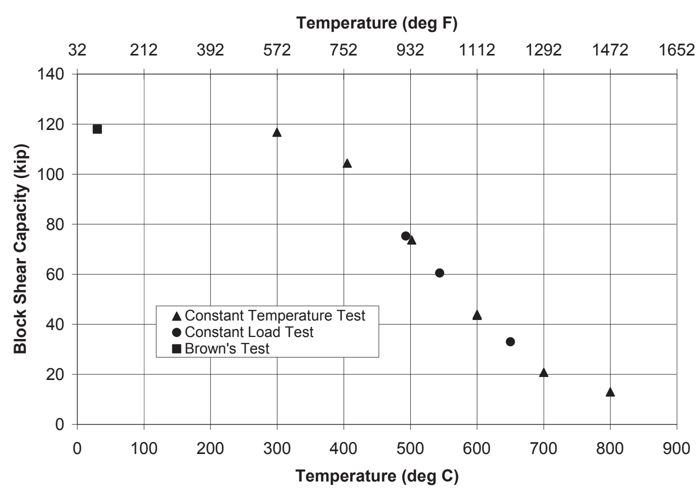


Fig. 15. Constant load test vs. constant temperature test (1 kip = 4.448 kN).

on A490 bolts at elevated temperature, the shear capacity of A490 bolt drops by 40% at 500 °C (932 °F) when compared with its shear capacity at ambient temperature (Yu and Frank, 2009). It is reasonable to estimate A490 bolt's tensile capacity drops by the same amount. From the mill test report, the tensile strength of this A490 bolt is 75.4 kips. At 500 °C (932 °F), the estimated tensile strength is 45.2 kips. The original pretension force is 57.3 kips, which is greater than estimated tensile strength of 45.2 kips at 500 °C (932 °F). Therefore, A490 bolt stretches plastically. After cooling to ambient temperature, the elongated bolt will have a reduced tension load, which would result in a loss of the slip capacity of the connection.

Figure 17 shows post-test slip surfaces of the connections that had been heated to different temperatures and cooled to ambient temperature before being tested for the slip capacity. On the slip surface of the control connections, slip marks are small. After the connection was heated to 100 °C (212 °F) and 200 °C (392 °F), large slip marks concentrate near the bolt hole, where high clamping force acts. This indicates better contact of the steel plate surfaces due to expansion and shrinkage in heating and cooling. At 300 °C (572 °F), there are more slip marks on the surfaces. These specimens had the highest slip load. At 400 °C (752 °F), slip marks reduce and are similar to the 100 °C (212 °F) connection. From 500 °C (932 °F) to 800 °C (1472 °F), slip marks almost disappear. This is consistent with the conclusion that A490 bolt loses most of its pretension force after experiencing temperature higher than 400 °C (752 °F).

COMPARISON WITH AISC SPECIFICATIONS

The bearing and block shear test results were normalized by dividing the strengths at elevated temperatures by the strength at room temperature. The results were compared

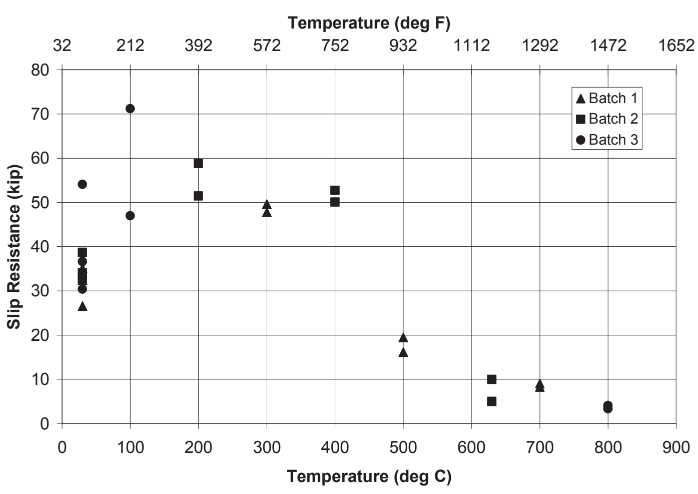


Fig. 16. Slip load vs. temperature (1 kip = 4.448 kN).

with the strength reductions of structural steels given in Table A-4.2.1 of the Appendix 4 of the AISC *Specification*, as shown in Figures 18 and 19. The results of the bearing test with bearing failures agree with the strength reduction factors in the AISC *Specification*. The AISC values overestimate the strength of connections, which failed by bolt shear failure. The heat-treated bolts have a rapid drop in strength when their temperature exceeds the tempering temperature during manufacture process, which results in a change from bearing failure to bolt shear failure. The block shear strength tests shown in Figure 19 all fall below the AISC strength curve. The block shear strength of the two-bolt connections during a fire would be overestimated using the AISC strength values at temperatures between 750 and 1300 °F (400 and 700 °C). If lower-strength A325 bolts had been used in these two-bolt connections, the strength would have been even lower since the test load exceeds the shear capacity of the A325 bolts. Both the strength of the bolts and plate material at the elevated temperature must be considered in determining the strength of the connection during a fire.

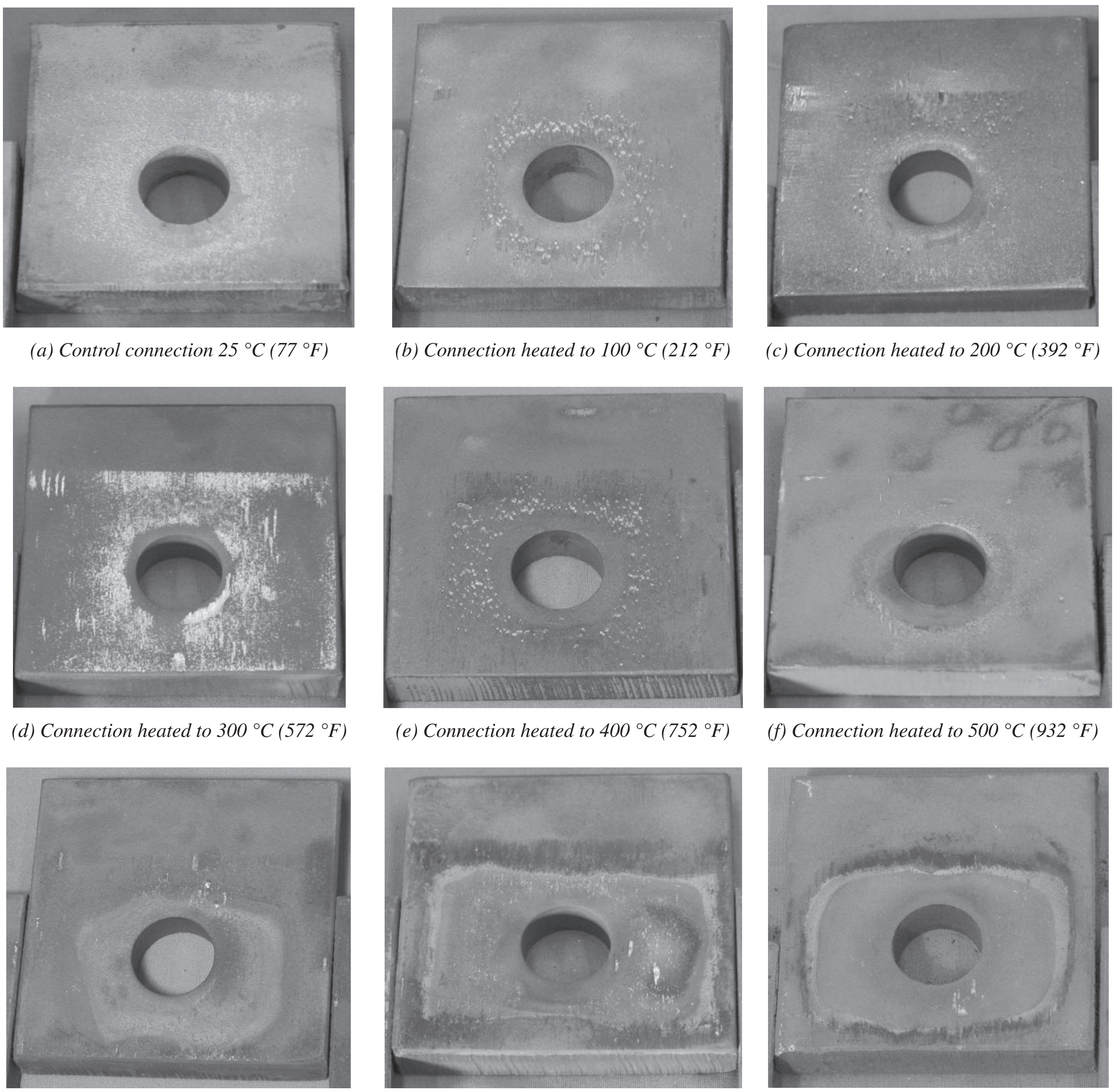
CONCLUSION

Single A325 bolt connections with two end distances, 1.0 and 1.5 times of the nominal bolt diameter, were tested at temperatures up to 800 °C (1472 °F). A 10 to 20% bearing capacity increase was found on all specimens at 300 °C (572 °F). As known from the milling process, steels exhibit a strength increase along with a ductility decrease around this temperature. A thorough explanation will involve the knowledge of metallurgy. For 1.0*d* connections, significant bearing capacity loss was found between 400 °C (752 °F) and 800 °C (1472 °F). On 1.5*d* connections, failure mode changed from bearing failure to shear failure of the bolt between 300 °C (572 °F) and 400 °C (752 °F). Above 400 °C (752 °F), load capacity of these connections was controlled by the shear capacity of the A325 bolts. Understanding this failure mode change is extremely important for improving the load capacity of bolted connections at elevated temperatures. At ambient temperature, the capacity of the tested connections was controlled by bearing strength of the bolt hole. However, at temperatures above 300 °C (572 °F), the shear capacity of the bolt becomes the controlling limit. Under such situation, increasing the end distance of bolt hole or plate thickness will not increase the load capacities of the connections.

Block shear capacity of bolted connections at elevated temperature was studied on two-bolt connections. Significant reduction on block shear capacity was found between 400 °C (752 °F) and 800 °C (1472 °F). Test results from constant load tests agree well with those from constant temperature tests. This indicates the constant temperature test results can be used to estimate the behavior of bolted connections regardless of the time-temperature history that the connection experiences during a fire event.

The residual slip load capacity of fully tightened A490 bolt connections was investigated. Up to 50% slip load capacity increase is found on the connections that were exposed to a temperature between 100 °C (212 °F) and 400 °C (752 °F). However, a 50% slip load capacity loss occurs after the exposure to 500 °C (932 °F). Further decrease is found after the specimen was exposed to temperatures between 500 °C (932 °F) and 800 °C (1472 °F). In addition, 400 °C (752 °F) is a key temperature in assessing the slip load capacity of A490 bolt after a fire. Connections heated below this temperature retain their slip capacity after a fire, while connections heated above this temperature have a reduced slip load capacity.

These findings provide an insight into the design of bolted connections at elevated temperatures and assess fire damage on bolt connections. The capacity of bolt connections



(a) Control connection 25 °C (77 °F) *(b) Connection heated to 100 °C (212 °F)* *(c) Connection heated to 200 °C (392 °F)*

(d) Connection heated to 300 °C (572 °F) *(e) Connection heated to 400 °C (752 °F)* *(f) Connection heated to 500 °C (932 °F)*

(g) Connection heated to 600 °C (1112 °F) *(h) Connection heated to 700 °C (1292 °F)* *(i) Connection heated to 800 °C (1472 °F)*

Fig. 17. Slip surface of connections after heated to different temperature levels and tested at room temperature.

are generally controlled by the bearing or block shear failure in the steel plates at temperatures below 300 °C (572 °F) because the heat-treated bolts have higher strength than structural steels; however, when exposed to temperatures above 300 °C (572 °F), the bolts lose their strength at a much higher rate than structural steels. The capacity of bolted connections becomes controlled by the strength of bolts rather than the steel plates. In other words, increasing the bolt end distance may not help the connection strength at temperatures above 300 °C (572 °F). For slip critical connections with fully tightened bolts, the load capacity can be greatly reduced after exposure to a temperature above 400 °C (752 °F).

The material strength reduction factors given in Appendix 4 of the AISC *Specification* follow the trend of the test results. However, the strength of the block shear tests was lower than the AISC strength reduction factors. The AISC strength values overestimated the strength of the bearing tests, which failed by bolt shear as well.

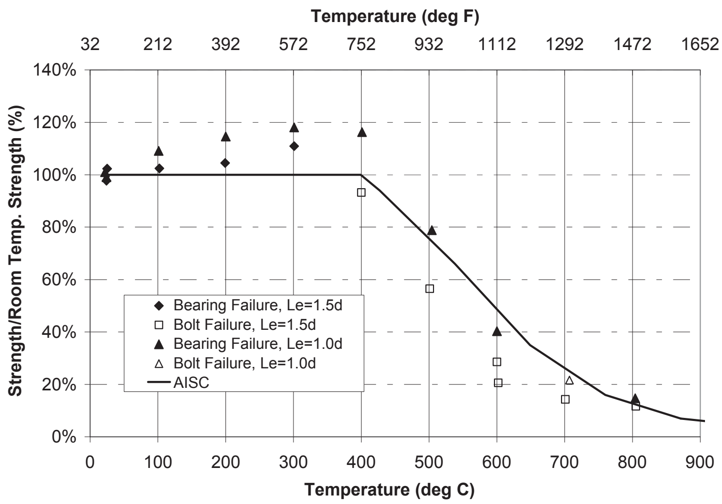


Fig. 18. Comparisons of bearing tests with AISC Appendix 4.

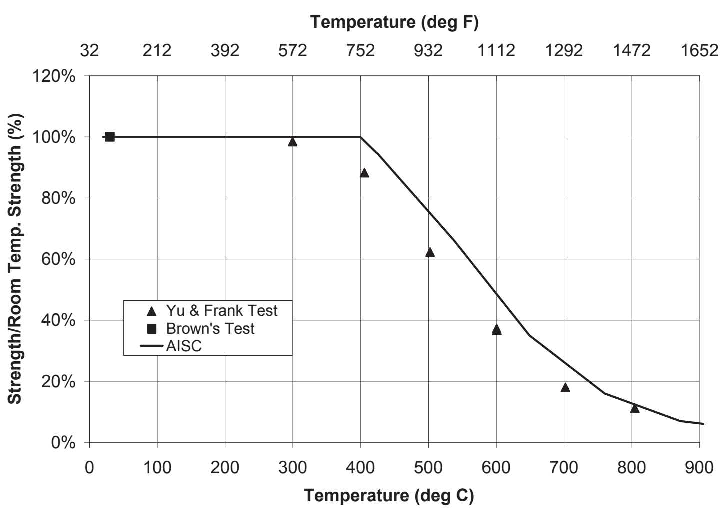


Fig. 19. Comparisons of block shear tests with AISC Appendix 4.

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