

Shear Behavior of A325 and A490 High-Strength Bolts in Fire and Post-Fire

LIANG YU and KARL H. FRANK

ASTM A325 and A490 bolts are widely used in bolted connections of steel structures. The strength of these heat-treated high-strength bolts at elevated temperatures is needed to determine their behavior in a fire. Understanding their response to elevated temperature is the key information required to evaluate the strength of bolted connections during a fire. The residual strength of a bolt after a fire is also important in assessing fire damage on a structure and the strategy for remediation of the structure after a fire.

Shear tests at elevated temperature were carried out on A325 and A490 bolts to investigate their change in stiffness and strength with temperature. Direct shear tests were used to determine the residual bolt strength after exposure to elevated temperatures. The shear tests were correlated with the results of hardness test of the bolts.

TEST SPECIMEN

ASTM A325 and A490 bolts, with ASTM F436 washers and ASTM A563 Grade DH nuts were tested (see Figure 1). All bolts in this test program had a nominal diameter of $\frac{7}{8}$ in., and a length of $7\frac{1}{2}$ in. Table 1 gives the mechanical properties of the bolts. The tensile strength listed is from the certified material test reports (CMTR). The results of room temperature shear tests on unthreaded shank of the bolt are also listed. The hardness tests reported in the CMTR and the results for the tests done on the test samples are also listed. Table 2 gives the chemical composition of the bolts as listed in the CMTR, and from a sample analyzed at an independent laboratory. Table 2 also gives the chemical composition of two sets of ISO Grade 8.8 bolts which were tested by B.R. Kirby in an earlier study (Kirby, 1995).

High-strength bolts are manufactured by annealing, cold forging of the head, rolling or cutting of the threads, and quenching and tempering to produce the required strength.

Due to the variations in chemical compositions in steel rod used to make the bolts, the manufacturing tempering temperatures may be adjusted to provide final products that meet the ASTM strength and hardness requirements (ASTM A325-04; ASTM A490-04). Variations in the chemical composition and tempering process may affect the bolts behavior at elevated temperature and their residual strength after exposure to a fire. To reduce the variability of the results, all of the bolts came from the same production lot.

TEST SETUP

Shear Test at Elevated Temperature

The high-temperature test system consists of an electric furnace, stainless steel loading clevises, load frame, hydraulic ram, and data acquisition equipment. Figure 2 shows the arrangement for the elevated temperature double-shear bolt tests.

Specimen temperature was monitored by two type K thermocouples attached at both ends of the bolt. The average temperature of the readings from both thermocouples was taken as the specimen temperature. The resolution of temperature readings is ± 0.1 °C (± 1.8 °F). Figure 3 shows the furnace heating curve along with the ASTM standard fire curve (ASTM E119-00a). The heating curve was much slower than the standard fire test used to determine a fire rating for a product or system. The purpose of these tests was not to develop a fire rating but rather to establish the strength of the bolts when they reach a certain temperature. The average heating rate was about 2.0 °C/min (3.6 °F/min). Load was applied by hydraulic ram using a pneumatic pump to supply the hydraulic pressure when the test temperature was

Liang Yu is senior engineer, Deepflex, Inc., Houston, TX.
Karl H. Frank is professor, department of civil, architectural and environmental engineering, University of Texas at Austin, Austin, TX.

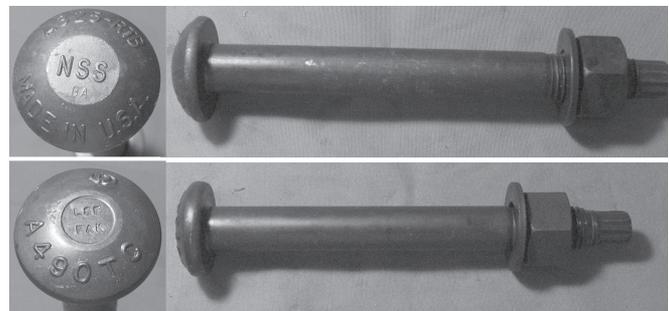


Fig. 1. A325 and A490 specimen bolts.

Table 1. Mechanical Properties and Geometries of Tested A325 and A490 Bolts				
Item	A325		A490	
	CMTR Tensile	Shear Strength	CMTR Tensile	Shear Strength
Strength (ksi)	134.8	84.3	163.5	106.7
Hardness (HRC)	CMTR – 28~32 Test Bolts – 30		CMTR – 35 Test Bolts – 37	

Table 2. Chemical Composition of Specimen A325 and A490 Bolts												
Bolt	Data Source	Chemical Composition (wt%)										
		C	Si	Mn	P	S	Cr	Mo	Ni	B	Cu	N
ASTM A325	CMTR	0.31	0.23	0.76	0.005	0.010	–	–	–	–	–	–
	Test Sample	0.29	0.27	0.76	0.006	0.010	0.05	0.010	0.06	0.0009	0.12	0.026
ASTM A490	CMTR	0.35	0.21	0.75	0.012	0.009	1.02	0.19	0.02	–	–	–
	Test Sample	0.36	0.24	0.76	0.015	0.009	1.13	0.180	0.04	<0.0005	0.03	0.023
ISO R898 8.8	Kirby 1995 Set A	0.19	0.21	1.16	0.020	0.017	0.19	0.027	0.14	0.0051	0.22	0.0080
ISO R898 8.8	Kirby 1995 Set C	0.41	0.16	1.61	0.021	0.038	0.13	0.130	0.12	<0.0005	0.23	0.013

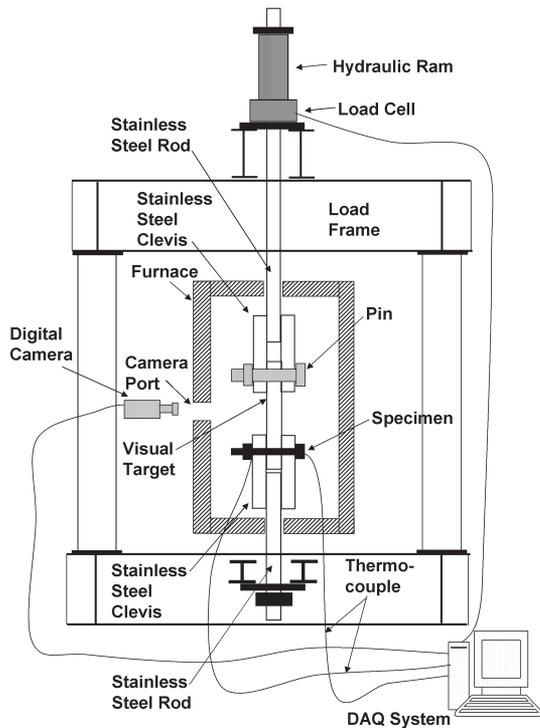


Fig. 2. Test setup for double-shear test on bolt at elevated temperature.

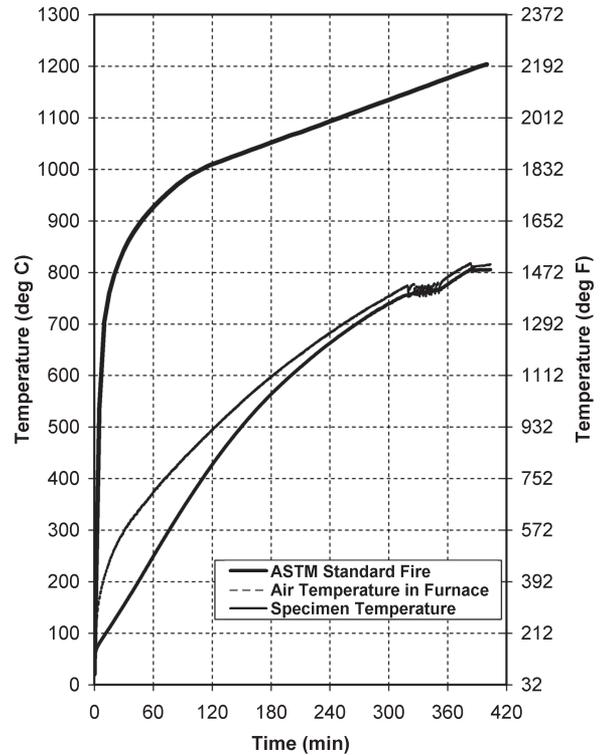


Fig. 3. Time-temperature curve of furnace.

reached. The load was measured by a 200 kip load cell with $\pm 0.1\%$ accuracy. Noncontact machine vision technology is used in measuring shear deformation of a specimen bolt. A $\frac{1}{16}$ -in.-diameter hole was drilled on a center loading plate to provide a visual target. A digital video camera was used to take real-time images through an observation port. Deformation was obtained by custom software. The resolution of the measured displacement was 0.005 in.

All the tests were conducted at constant temperature with quasi-static loading until failure. The test bolt was inserted through the holes into the bottom of the clevis plates and the center plate. The specimen bolt was then tightened by hand to minimize transmission of the shear force by friction. Both shear planes were in the unthreaded shank of the bolt. The specimen bolt was heated to the desired temperature level and held at the temperature to ensure uniform temperature distribution before the load was applied to the specimen. The shear load is applied by the hydraulic ram attached to the center plate by a stainless steel rod. The shear failures on both shear planes occurred simultaneously and symmetrically, which indicated the load was distributed evenly between the two shear planes. Therefore, half of the maximum load recorded in these double-shear tests by the load cell is taken as the single-shear capacity of the bolt. A minimum of two tests were performed at each temperature level for each bolt type. If the results were scattered, a third test was performed to confirm the test results.

Residual Strength Test Procedure

Both direct shear tests and hardness tests were carried out at ambient temperature to investigate residual strength of the bolts after exposure to elevated temperature. The direct shear test was performed with a single-shear fixture shown in the bottom left of Figure 4 using a test machine to apply the shear load. The hardness testing was performed on the

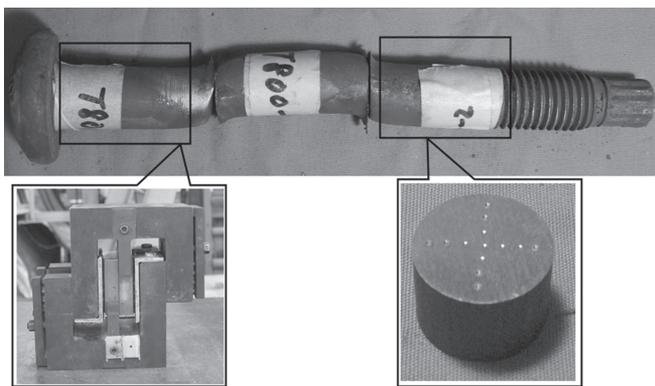


Fig. 4. Bolt segments for direct shear test and hardness test.

machined and polished section of the shank of the bolt in a standard Rockwell hardness tester. The bolt segments used in both shear and hardness tests were obtained from the undeformed region of the bolts that had been tested at elevated temperature. Figure 4 shows the portion of the bolts used for direct shear test and hardness tests. The hardness test points on bolt section are also shown.

EVALUATION OF TEST RESULTS

Shear Strength at Elevated Temperature

The double-shear tests on A325 and A490 bolts were performed from 25 to 800 °C (77 to 1,470 °F) in 100 °C (180 °F) increments. Figure 5 shows load-displacement curves of A325 bolt shear tests from 25 to 700 °C (77 to 1290 °F). Due to a malfunction of the data acquisition system, the displacement data are not available for the tests performed at 800 °C (1470 °F). However, the load data were recorded properly. From 25 to 200 °C (77 to 390 °F), the initial shear stiffness of the A325 bolt is not affected by the test temperature. A slight strength increase occurs at 200 °C (390 °F), the blue brittle temperature range of steel, and the load displacement curve ends abruptly at peak load. From 400 to 700 °C (750 to 1290 °F), both the strength and stiffness of A325 bolt drops dramatically with temperature. The long unloading part on load-displacement curve reveals increased ductility of bolt at these temperatures.

Figure 6 gives the load-displacement curves of double-shear tests on A490 bolt from 33 to 800 °C (90 to 1470 °F). From 33 to 200 °C (90 to 390 °F), the strength of A490 bolt decreases slightly with temperature and reaches a minimum at 200 °C (390 °F). The strength then increases at 300 °C (570 °F). From 400 to 800 °C (750 to 1470 °F), the A490 bolt

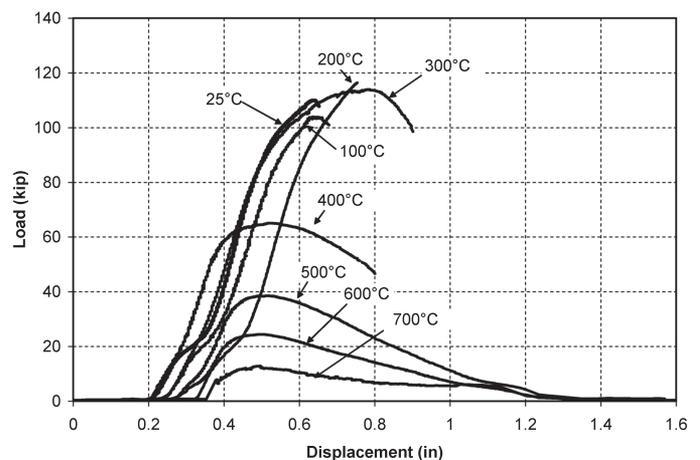


Fig. 5. Load-displacement curves of double-shear test on A325 bolt.

behaves similarly to the A325 bolt with both the strength and stiffness decreasing and the ductility increasing with increasing temperature.

Shear strengths of A325 and A490 bolts at elevated temperatures are shown in Figure 7. The shear capacity of A325 bolts changed slightly below 300 °C (570 °F) with maximum value at 200 °C (390 °F). Between 300 °C and 700 °C (570 °F and 1290 °F), shear capacity dropped dramatically with temperature. The shear capacity remains constant between 700 °C and 800 °C (1290 °F and 1470 °F). From 33 to 300 °C (90 to 570 °F), shear capacity of A490 bolt drops by about 5% at 200 °C (390 °F) first and then comes back at 300 °C (570 °F). Beyond 300 °C (570 °F), shear capacity drops almost linearly with temperature. At 400 °C (752 °F), 500 °C (932 °F), 600 °C (1110 °F) and 700 °C (1290 °F), the shear capacity drops by 17%, 40%, 65% and 85%, respectively.

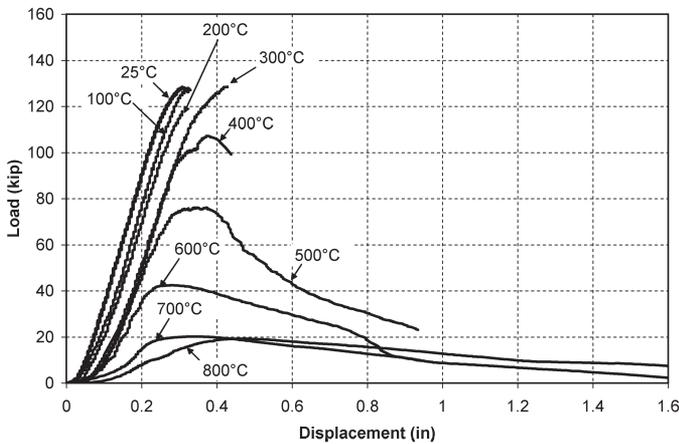


Fig. 6. Load-displacement curves of double-shear tests on A490 bolts.

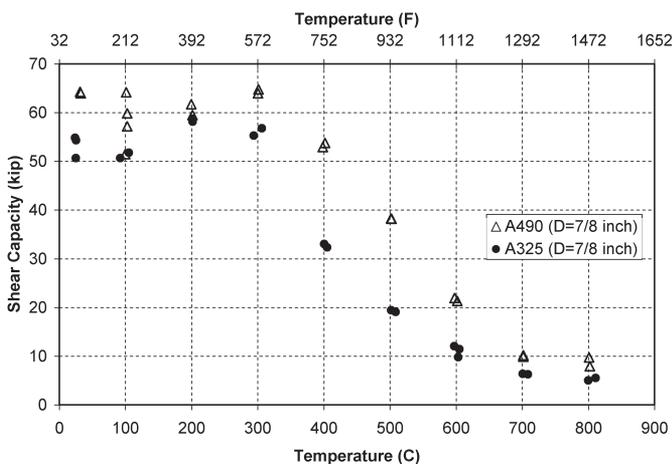


Fig. 7. Shear capacities of A325 and A490 bolts at elevated temperatures.

From 700 to 800 °C (1290 to 1470 °F), the shear capacity is essentially constant. Replicate test results are very consistent at all temperature levels for both types of bolts except for the A490 bolts tested at 100 °C (210 °F).

The shear strength relative to the room temperature capacity provides a means of developing design values at elevated temperatures. The relative shear capacity, or normalized shear capacity, is defined as the ratio of the shear capacity at elevated temperature to the shear capacity at ambient temperature. Figure 8 gives the normalized shear capacity of both types of bolts. Differences in the behavior of bolt types are evident in two temperature ranges. One is near 200 °C (390 °F), where A325 bolt has about 15% higher normalized shear capacity than A490; the other is from 300 to 700 °C (570 to 1290 °F), where the A490 bolts have significantly higher relative shear capacity than the A325 bolts.

Kirby performed a series of double-shear tests on a M20 Grade 8.8 high-strength bolt, the metric equivalent to an A325 bolt, at elevated temperature levels (Kirby, 1995). Two different lots of bolts, lot A and lot C, were tested. The chemical compositions of these two lots of bolts are given in Table 2.

Figure 9 shows the normalized shear capacity of A325, A490 and Grade 8.8 bolts. It is found that A490 bolt behaves very similarly to Grade 8.8 bolts, while A325 bolt does not. From ambient temperature to 300 °C (570 °F), A490 and Grade 8.8 bolts exhibit similar behavior. The A325 bolt shows a unique peak at 200 °C (390 °F). From 300 to 600 °C (570 to 1110 °F), the A490 bolt has a higher strength than the Grade 8.8 bolts. In the same temperature range, the A325 bolt shows significantly lower strength than the other three bolts. The difference in molybdenum contents between the bolts may be the cause of this difference in elevated temperature strength. Molybdenum can greatly increase steel

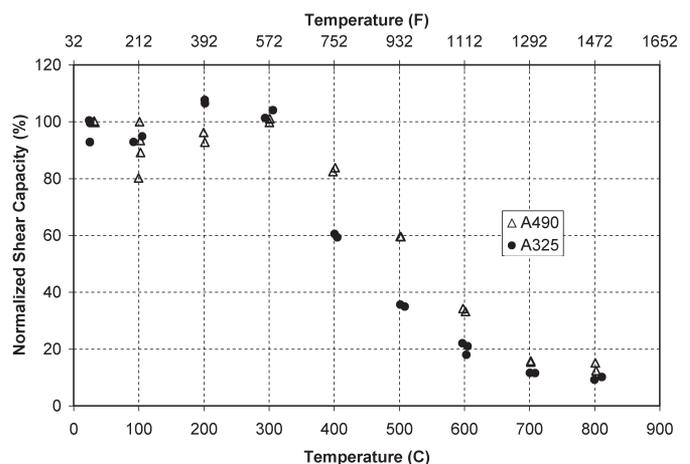


Fig. 8. Relative shear capacity of A325 and A490 bolts at elevated temperature.

strength at medium temperature range (Honeycombe, 1981; DeGarmo, 1979). The molybdenum contents of A490, Set C, Set A and A325 bolts are 0.180%, 0.130%, 0.027% and 0.010%, respectively, which corresponds to the sequence of normalized strength from high to low in the temperature range of 300 to 600 °C (570 to 1110 °F). At 700 °C and 800 °C (1290 °F and 1470 °F), the normalized shear capacity of the four groups of bolts converged to 12 to 15% of the room temperature value. Careful readers may notice that the four groups of bolts have significant differences in other alloy contents, such as carbon, manganese and boron, as well. Because those three alloy elements mainly affect the hardenability of steel but not the strength at elevated temperatures, the normalized shear strength shows no correlation with the percentage of those elements.

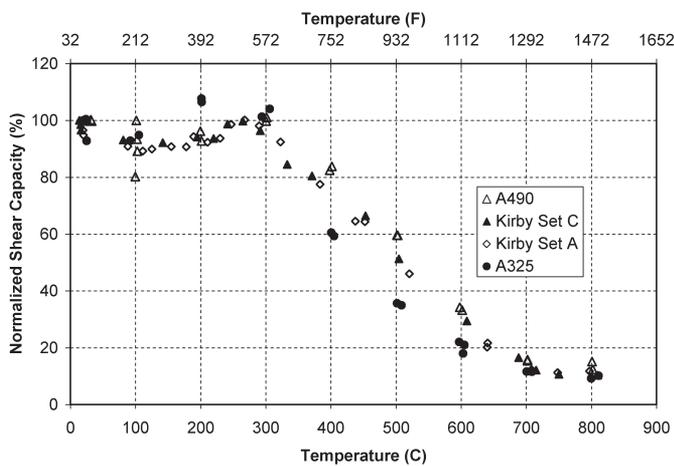


Fig. 9. Comparison of A325 and A490 high-strength bolts with Grade 8.8 M20 high-strength bolts.

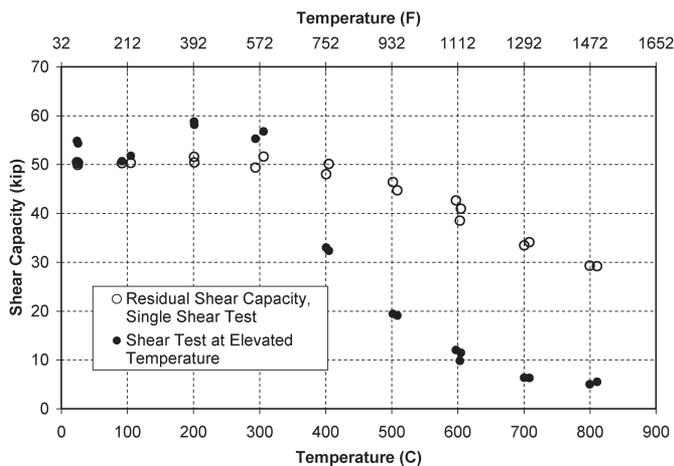


Fig. 10. Elevated temperature and residual shear capacity of A325 bolts.

Residual Shear Capacity Post-Exposure to Elevated Temperature

Figure 10 compares the residual shear capacity of A325 bolts with their shear capacity at corresponding elevated temperature levels. The tests show that if an A325 bolt is exposed to a temperature lower than 400 °C (750 °F), the bolt strength is fully recovered after cooling back to ambient temperature. A bolt exposed to a temperature higher than 400 °C (750 °F) has a lower strength after returning to ambient temperature. The A325 bolt loses strength linearly after heating to temperatures between 400 °C and 800 °C (750 °F and 1470 °F). The residual strength was about 55% of the room temperature strength after exposure to 800 °C (1470 °F). It is very interesting that the shear strength at temperatures of 200 °C and 300 °C (390 °F and 570 °F) are higher than the corresponding residual shear strength. The reason could be the changes steel microstructure in the blue brittle temperature range. This microstructure change may increase steel strength and decrease ductility (Honeycombe, 1981).

Figure 11 shows the residual shear capacity of A490 bolts along with their shear capacity at corresponding temperature levels. The A490 bolts behaved differently from A325 bolts. From ambient temperature to 300 °C (570 °F), A490 bolts had residual shear capacity close to the shear capacity at the elevated temperature, which was slightly above the initial room temperature strength. The A490 bolt showed no loss of strength after being subjected to temperature of 500 °C (930 °F). Above 500 °C (930 °F), the A490 bolt lost its strength linearly as the exposure temperature increased. The shear strength of the A490 bolts was 60% of the original room temperature strength after heating to 800 °C (1470 °F).

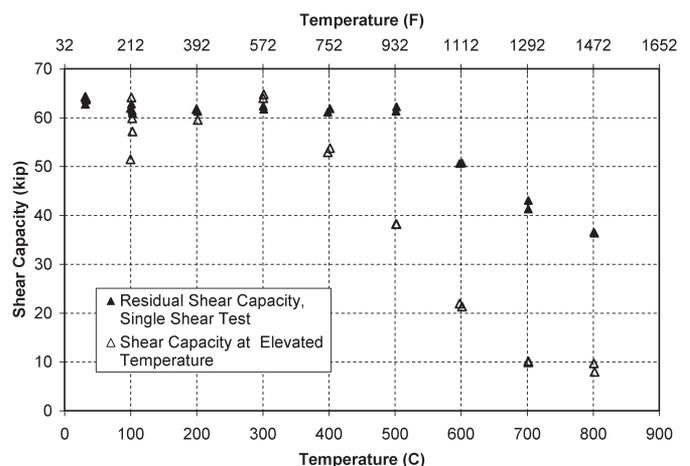


Fig. 11. Elevated temperature and residual shear capacity of A490 bolts.

Table 3. Estimated Residual Tensile Strength with Different Cooling Rate			
Estimated Tensile Strength (ksi)	Cooling Method		
	In Room Air	In Ice Water	In Furnace
Bolt #1	113	112	111
Bolt #2	105.0	–	103.7

The strength of heat-treated bolts decreased because the temperature they were exposed to was higher than the tempering temperature during manufacturing (DeGarmo, 1979). The heating of a bolt to a temperature above tempering temperature re-temper the bolt to a lower strength level. Exposure to temperatures below the tempering temperature does not reduce the strength of the bolts. The tempering temperatures of the bolts tested in this study are estimated to be 400 °C and 500 °C (750 °F and 930 °F), respectively, for the A325 and A490 bolts.

Hardness testing of the bolts was examined as an alternative method to estimate residual strength. Hardness testing does not require special shear test fixture and is much simpler to perform. The process involves using hardness measurements to estimate the tensile strength of the fastener. The tensile strength was estimated using Table 2 and Table 3 in ASTM A370 (ASTM, 2003). The shear strength was estimated by multiplying the estimated tensile strength by 0.6 to approximate the shear strength of the fastener and then multiplying by the gross area of the bolt. The results were compared with single-shear test results.

Figures 12 and 13 show the estimated residual shear capacity of A325 and A490 bolts based upon area weighted hardness and hardness at the quarter diameter location, $\frac{1}{2}R$,

along with the results from single-shear tests. For both types of bolts, the shear capacity estimated from the hardness tests provides a very good estimate of the direct single-shear test results from ambient temperature to 600 °C (1110 °F). Estimated shear capacity was conservative, compared with shear test results, at 700 °C and 800 °C (1290 °F and 1470 °F). For both types of bolts, the hardness value at the $\frac{1}{2}R$ position, provided a good estimation of the area weighted hardness value for the whole section. Therefore, only a single set of measurements at mid-point between the center and edge of the bolt is needed to estimate the shear strength of the bolt after a fire.

The effect of duration that a bolt is exposed to elevated temperature on its residual strength was also investigated. Two A325 bolts were cut into five segments each and exposed to 600 °C (1110 °F) for different lengths of time. After being cooled to ambient temperature, hardness tests were performed. The estimated tensile strength based upon the hardness versus the length of time that it was kept at 600 °C (1110 °F) is plotted in Figure 14. It is found that an additional 330 minutes (5.5 hours) of exposure at 600 °C (1110 °F) results in an additional 10% reduction in tensile strength for these A325 bolts.

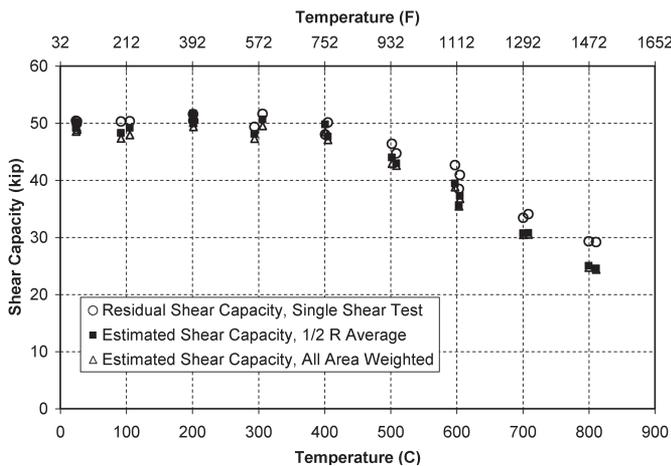


Fig. 12. Estimated residual shear capacity of A325 bolts.

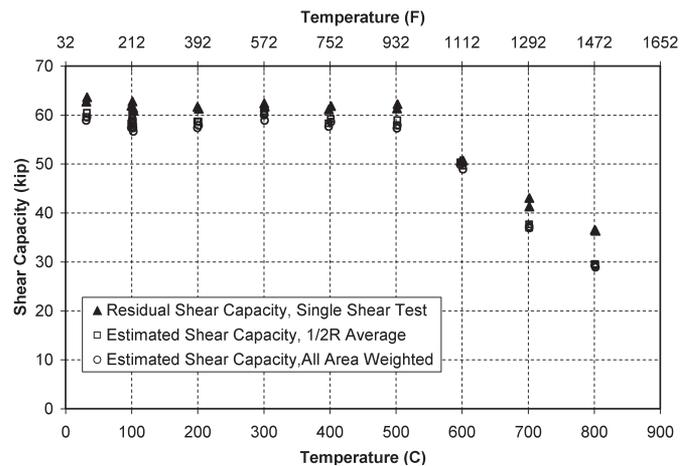


Fig. 13. Estimated residual shear capacity of A490 bolts.

Table 4. Shear Strength Reduction Factor for Tested A325 and A490 Bolts at Elevated Temperatures					
A325			A490		
Temperature (T_a)		Reduction Factor	Temperature (T_a)		Reduction Factor
°C	°F		°C	°F	
25	77	1.00	32	89	1.00
99	209	0.96	101	214	0.91
202	396	1.00	200	393	0.95
300	572	1.00	301	573	1.00
403	757	0.61	400	752	0.83
506	943	0.36	502	935	0.60
600	1112	0.21	600	1111	0.34
705	1301	0.12	702	1295	0.16
803	1477	0.10	801	1475	0.14

The effect of the cooling rate on the bolts residual strength was also studied. Segments from one A325 bolt were heated to 600 °C (1110 °F) for 6 hours and then cooled in room air, in ice water, and in a furnace. The time for the bolt segment temperature to reach room temperature is estimated to be 30 minutes, 5 seconds and 12 hours for these three conditions. The results in Table 3 show that the cooling rate has no effect on the residual tensile strength of A325 bolt.

CONCLUSIONS

Shear tests on ASTM A325 and A490 bolts were carried out from ambient temperature to 800 °C (1470 °F). From both types of bolts, the strength and stiffness of the bolts reduce

between 300 °C and 700 °C (570 °F and 1290 °F). Table 4 summarizes the strength reduction factors from test results, which can be used to estimate the shear strength of bolted connection in a fire.

The residual strength of A325 and A490 bolts after a fire or after exposure to elevated temperature was investigated with both direct shear test and hardness test. Both types of bolts lose strength when heated above tempering temperature used in heat treatment of the bolts. The maximum strength loss for A325 and A490 bolt after exposure to 800 °C (1472 °F) are about 45% and 40%, respectively. Simple hardness test of a bolt after a fire can be used to estimate the shear strength of the bolt.

An experimental study on A325 bolt showed that the duration of exposure to elevated temperature has a limited effect on residual strength. The cooling rate has almost no effect on residual strength.

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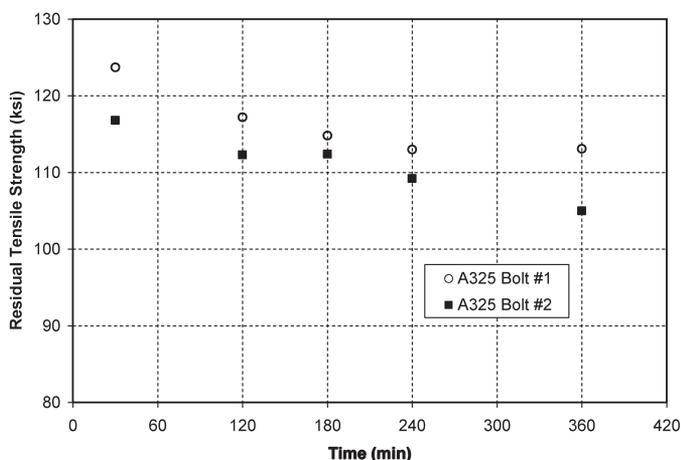


Fig. 14. Estimated residual tensile strength vs. duration of exposure to elevated temperature.

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