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Double-shear tests of high-strength structural bolts at elevated temperatures

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ABSTRACT

The behavior of high-strength structural steel at elevated temperatures, especially under shear loading, is not well established in the literature. This paper presents results from recently conducted tests on high-strength structural bolts subject to double shear loading at elevated temperatures. The parameters varied between tests included the bolt grade, bolt diameter, and temperature. Bolt grades A325 and A490 were tested. For each bolt grade, three different diameters were tested (19 mm (3/4 in), 22 mm (7/8 in), and 25.4 mm (1 in)) at five different temperatures (20 °C, 200 °C, 400 °C, 500 °C, and 600 °C). At least three tests were conducted for each combination of parameters. Degradations in the mechanical and material properties including stiffness, strength, and deformation at fracture, are characterized and presented herein. The results from these experiments fill a critical knowledge gap currently present in the literature regarding the behavior of high-strength structural bolts under shear loading at elevated temperatures. These data will ultimately provide a thorough understanding of the overall behavior of structural steel systems under realistic fire loading by clarifying the (i) shear behavior of high-strength structural steel bolts at elevated temperatures, and (ii) degradation in the mechanical and material properties of high-strength steel bolts with increasing temperatures.

1. Background

Fire effects on steel structures can produce failures of connections, including fracture of connection plates, shear rupture of bolts, and bolt tear-out failure of beam webs or connection plates. Seif et al. [1] and [2] examined such failure modes for typical shear and moment connections at elevated temperatures, based on explicit high-fidelity finite element analyses. Whether such failures occur depends not only on the loads that can be sustained by the various components of a connection, but also on the deformations that can be accommodated prior to fracture, since fire-induced forces result from the restraint of thermal expansion or contraction. The ductility of steel components plays an important role in the performance of connections at elevated temperatures. Sufficient ductility can potentially allow redistribution of loads after failure of one or more connection components.

Thus, a key issue in evaluating the response of structural systems to fire effects is the proper representation of material behavior, including fracture, at elevated temperatures. Temperature-dependent material behavior of structural plate materials (such as ASTM A36, ASTM A572, and ASTMA992), has been studied both experimentally and numerically (e.g., Seif et al. [3,4], and Hu et al. [5]). However, the behavior of high-strength structural bolts at elevated temperatures, especially under shear loading, is not well established in the literature. The current lack of reliable experimental data has made proper characterization of the temperature-dependent material behavior of bolts impossible, forcing researchers to use alternative approximations. Seif et al. [4] proposed a simple multi-linear representation of the temperature-dependent true stress-strain behavior for high-strength bolts.

Kodur et al. [6] studied the influence of elevated temperatures on the thermal and mechanical properties of steel bolts, including a limited number of experiments on bolts under tensile loading at different temperatures. Yu [7] studied the effect of high temperatures on bolted connections. His work included a few experiments on bolts under shear loading, and he noted that if a bolt is not heated up past its tempering temperature, its shear resistance is not affected. However, the experiments were limited to a small set of data, with excessive bearing deformations imbedded in the results. Thus, a more comprehensive set of test data was needed in order to provide a fuller understanding of the behavior of high-strength bolts under shear loading at elevated temperatures, which will ultimately lead to a fuller understanding of the overall behavior of structural steel systems under realistic fire loading. The following sections describe the details of this experimental study along with the results and discussion.

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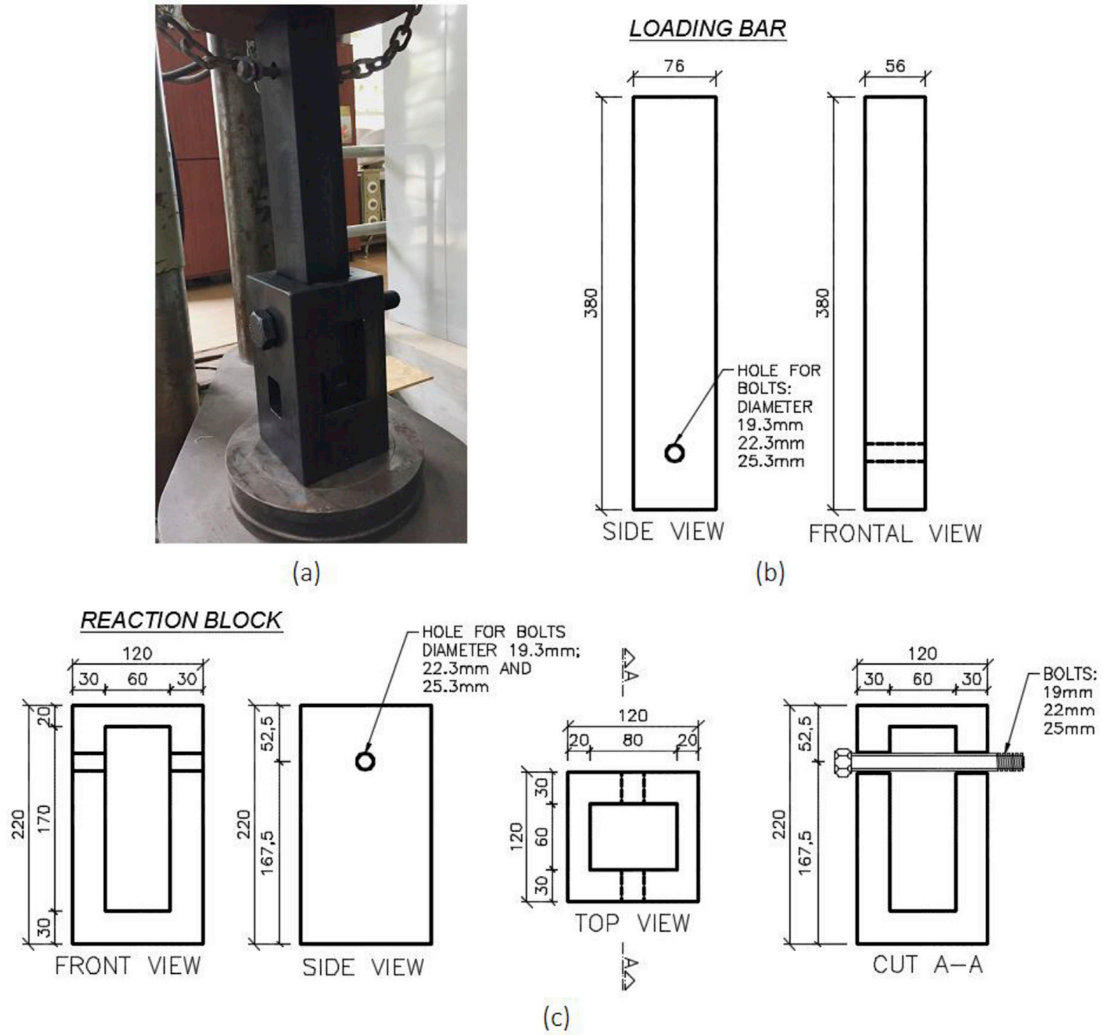

Fig. 1. Test block: (a) photo of actual setup, (b) and (c) dimensions. All dimensions are in mm (1 in = 25.4 mm).

2. Test parameters and setup

The parameters varied between tests included the bolt grade, bolt diameter, and temperature. Bolt grades ASTM A325 [8] (specified nominal yield strength of 635 MPa (92 ksi) and specified nominal ultimate strength of 825 MPa (120 ksi)) and ASTM A490 [8] (specified nominal yield strength of 895 MPa (130 ksi) and specified nominal ultimate strength of 1035 MPa (150 ksi)) were tested. For each bolt grade, three different diameters were tested (19 mm (3/4 in), 22 mm (7/8 in), and 25.4 mm (1 in)) at five different temperatures (20 °C, 200 °C, 400 °C, 500 °C, and 600 °C). At least three tests were conducted for each combination of parameters. Degradations in the mechanical and material properties including stiffness, strength, and deformation at fracture, were documented and are presented in the following sections.

All specimens were tested in a specially manufactured testing blocks, heated to the specified temperature, and then subjected to double-shear loading. The testing blocks were designed to resist loads much higher than the bolts' nominal shear capacity, and were reused for multiple tests. Two sets of testing blocks were manufactured: one set for the 19 mm (3/4 in) and 22 mm (7/8 in) diameter bolts, and one set for the 25 mm (1 in) diameter bolts. The first set was manufactured using ASTM A36 steel [9] (yield strength of 250 MPa (36 ksi) and ultimate strength of 400 MPa (58 ksi)), and the second was manufactured using the heat treated AISI/SAE 8640 alloy steel [10] (yield strength of 560 MPa (81 ksi) and ultimate strength of 750 MPa (109 ksi)). For the 19 mm (3/4 in) and 22 mm (7/8 in) bolt diameter tests, the same set of testing blocks was used and only the hole necessary to pass the bolt was enlarged after all the 19 mm (3/4 in) bolts were tested. The configuration and dimensions of the testing blocks are shown in Fig. 1. Refer to section 4.1 for further discussion on the blocks.

The specified temperature for each test was reached by placing the entire test setup in an electric furnace which was capable of achieving a maximum temperature of 1200 °C. A rate of temperature loading of 20 ºC/min was used for all tests and the entire test setup was free to expand. One thermocouple type K was placed inside the furnace to control the furnace temperature and three additional thermocouples type K were strategically placed on the bolt specimens (touching the bolt surface) to ensure that the target temperature had been achieved in the bolt at the initiation of the shear loading. As stated by the thermocouple manufacturer, the precision of the measured temperature at 0 °C is of 2.2 °C. The shear loading on the bolt specimen was applied using a universal testing machine, which had a capacity of 980.7 kN (220.5 kip) and an uncertainty of measurement at 10 kN (2.25 kip) of ±0.1 kN, at a level of confidence of 95%. Compression loading was applied at a rate of approximately 60 kN/min (13.49 kip/

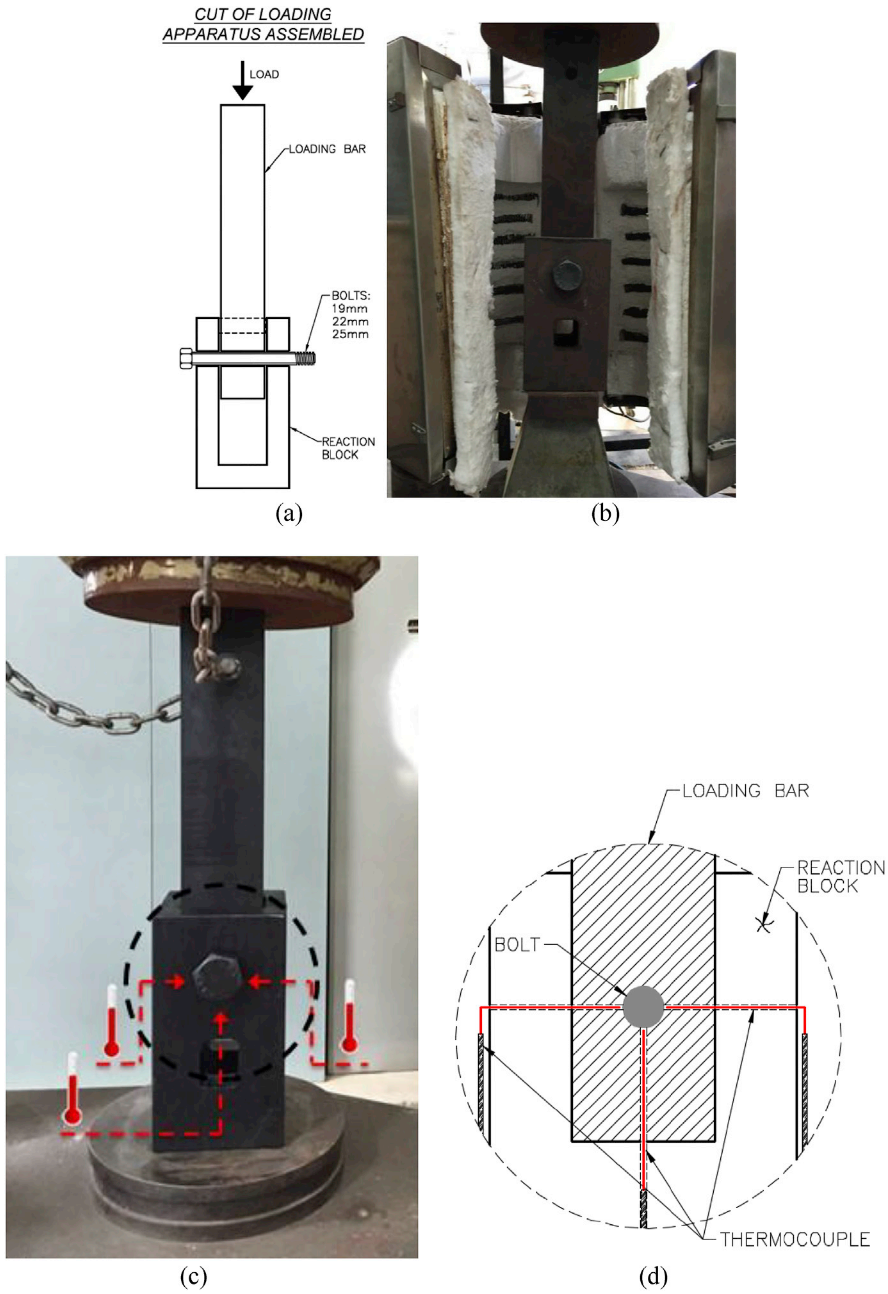

Fig. 2. Test setup: (a) load path, (b) furnace, (c) location of thermocouples, and (d) schematic location of thermocouples.

Table 1
Specimen dimensions.

Steel Grade	Diameter mm (in)	Length mm (in)
A325	19 (3/4)	203.2 (8.0)
	22 (7/8)	165.1 (6.5)
	25 (1.0)	203.2 (8.0)
A490	19 (3/4)	215.9 (8.5)
	22 (7/8)	165.1 (6.5)
	25 (1.0)	190.5 (7.5)

min) throughout the entire test. The loading was continued until the bolt ruptured in double-shear. The displacement of the universal testing machine was monitored using an external linear variable displacement transducer (LVDT), which had a range of 100 mm (3.94 in) and a precision of 1/1000 mm. The uncertainty in the displacement measurement was less than 0.1%. Double-shear was achieved by applying the load through the middle block, shearing the bolt through two shear-planes, as shown in Fig. 2a. Fig. 2b shows the furnace enclosing the test setup. Fig. 2c shows the location of the three additional thermocouples: one in the bottom, and one on each side of the tested bolt. All the three thermocouples were touching the bolt surface until shear failure of the bolt occurred. Throughout each test, temperature, force and displacement were recorded. The results are presented in the following section.

For the ambient temperature tests, when the furnace was not required, the bolts were tested at their entire length. The dimensions of the tested bolts are given in Table 1. For the elevated temperature tests, due to the limited space within the furnace, only a 165 mm (6.5 in) length of the bolt was tested, and the excess length of the bolt was cut off. For all

Table 2
Chemical Analysis of tested bolts samples[a].

TypeD (mm (in)) Element	A325			A490			A325 Type 1 Specification	A490 Type 1 Specification
	25 (1)	22 (7/8)	19 (3/4)	25 (1)	22 (7/8)	19 (3/4)		
	Mass Fraction							
C	0.0042	0.0044	0.0038	0.0033	0.0031	0.004	0.0030 to 0.0052	0.0030 to 0.0048
Mn	0.0098	0.0096	0.0084	0.0087	0.009	0.0092	0.0060 min	0.0060 min
P	0.00008	0.00008	0.00012	0.0001	0.00011	0.00008	0.00035 max	0.00035 max
S	0.00008	0.00008	0.00018	0.00006	0.00012	0.0001	0.0004 max	0.0004 max
Si	0.0023	0.0024	0.0023	0.002	0.0022	0.0021	0.0015 to 0.0030	ns
Ni	0.0005	0.0006	0.0006	0.0005	0.0008	0.0009	ns	ns
Cr	0.0031	0.0035	0.0037	0.0017	0.0023	0.0031	ns	ns
V	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	ns	ns
Mo	0.0022	0.0021	0.0003	0.0009	0.0009	0.002	ns	ns
Cu	0.0008	0.0008	0.0012	0.0007	0.001	0.0008	ns	ns
Al	0.0002	0.0002	<0.00005	0.0002	0.0003	0.0002	ns	ns
Nb	<0.00005	0.0001	<0.00005	<0.00005	0.0001	<0.00005	ns	ns
Ti	<0.00005	<0.00005	<0.00005	0.0002	0.0002	<0.00005	ns	ns
B	<0.00005	<0.00005	<0.00005	0	0	<0.00005	0.00003 max	0.00003 max

[a] ns = not specified.

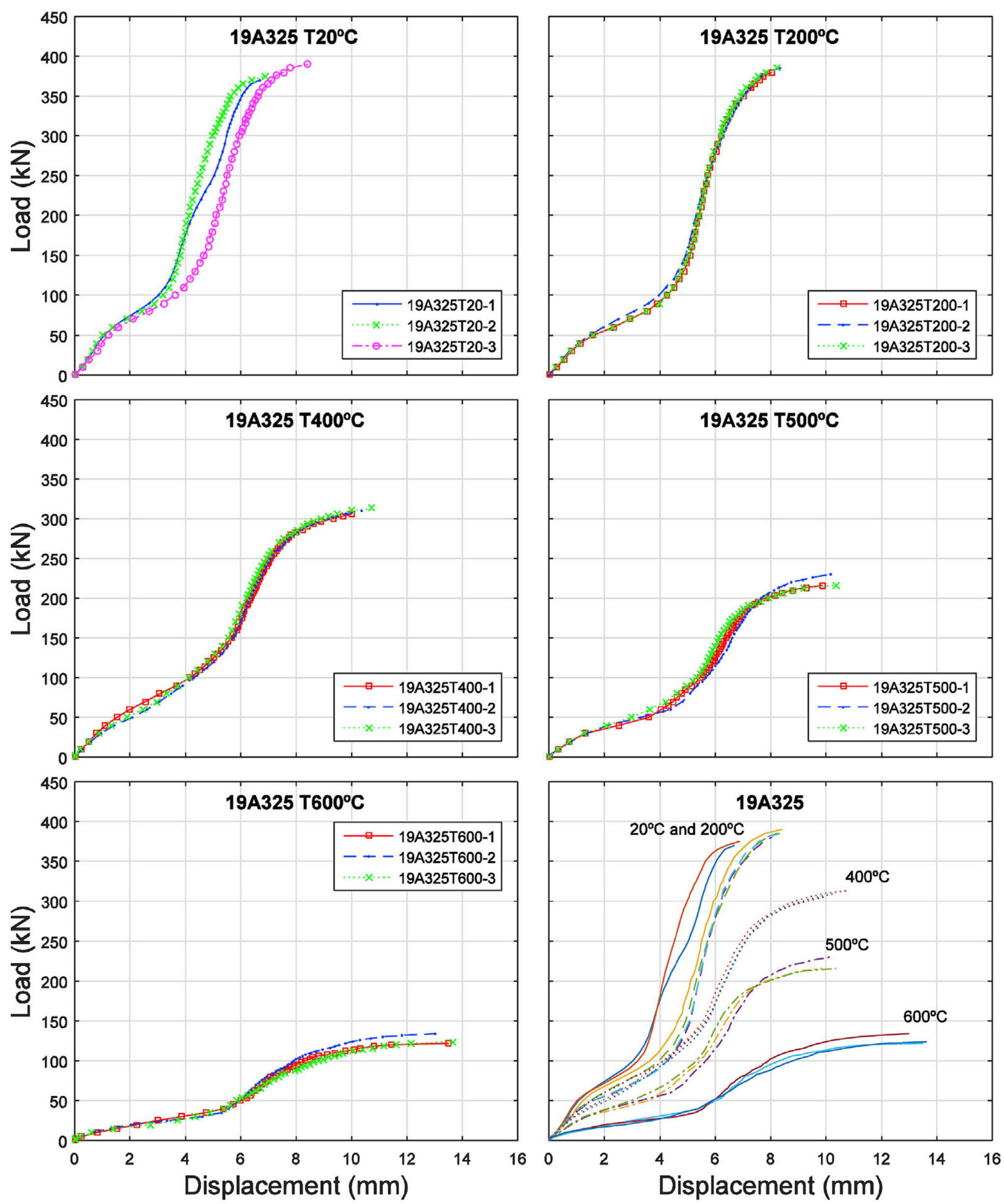

Fig. 3. Load versus displacement for the 19 mm (3/4 in) A325 bolts.

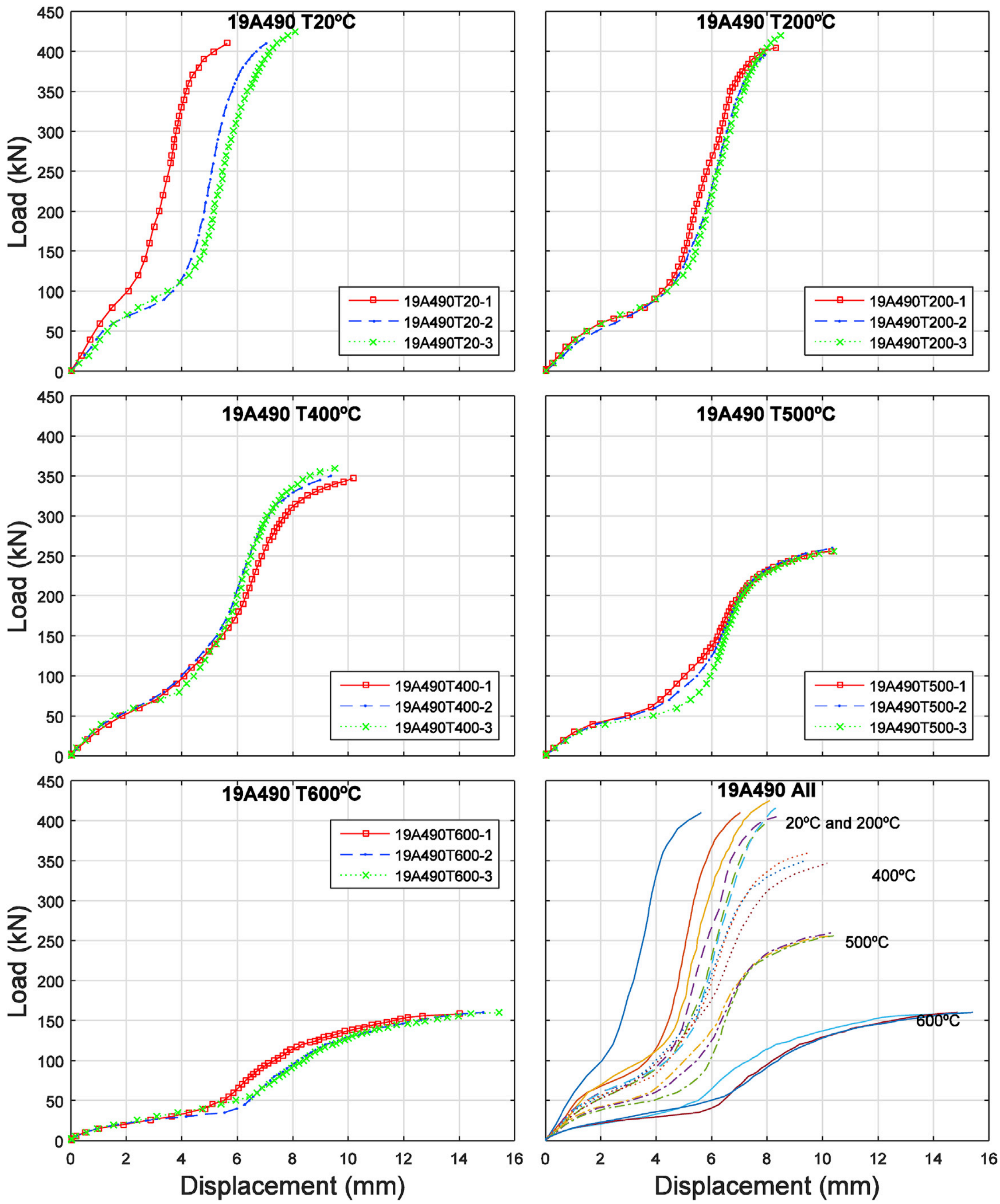

Fig. 4. Load versus displacement for the 19 mm (3/4 in) A490 bolts.

tests, both shear planes (within the 120 mm (4.7 in) width of block set) passed through the unthreaded portion of the bolt, and no thread-effect was tested or considered in this study. It is common practice to have the load path on bolts in connections pass through only unthreaded portions of the bolt.

Each test was assigned a unique name. The nomenclature includes the bolt, diameter, type, test temperature, and specimen number. For example, test "19A325T20-1". The first two digits represent the bolt diameter (19 mm (3/4 in), 22 mm (7/8 in), or 25.4 mm (1 in)), the next four characters represent the bolt type (A325 or A490), followed by the letter T and the temperature at which that bolt was tested (T20 = 20 °C (Ambient Temperature); T200 = 200 °C; T400 = 400 °C; T500 = 500 °C; T600 = 600 °C), and lastly, the number of the specimen.

A commercial laboratory analyzed the chemical composition of three of the A325 (one of each bolt diameter size) and three of the A490 bolts (one of each bolt diameter size) using the ASTM.

E1019 [11] and ASTM E415 [12] standard testing methods. Table 2 summarizes both the specified and as-analyzed chemistry. The chemistry of both sets of bolts corresponds to Type 1.

3. Experimental results

This section presents the experimental results for all of the ninety-one bolts tested under double-shear loading. Fig. 3 through Fig. 8 show the

Table 3
Results for 19 mm (3/4 in) bolt diameter experiments.

Specimen Name	Steel	Temperature (°C)	Failure Load kN (kip)	Displacement at Failure mm (in)
19A325T20-1	A325	20	372.0 (83.7)	6.69 (0.263)
19A325T20-2			375.0 (84.4)	6.88 (0.270)
19A325T20-3			391.5 (88.1)	8.41 (0.331)
19A325T200-1		200	383.9 (86.4)	8.03 (0.316)
19A325T200-2			392.0 (88.2)	8.33 (0.327)
19A325T200-3			388.6 (87.4)	8.24 (0.324)
19A325T400-1		400	309.8 (69.7)	10.02 (0.394)
19A325T400-2			312.1 (70.2)	10.36 (0.407)
19A325T400-3			314.0 (70.7)	10.74 (0.422)
19A325T500-1		500	217.6 (49.0)	9.87 (0.388)
19A325T500-2			232.4 (52.3)	10.16 (0.399)
19A325T500-3			216.3 (48.7)	10.36 (0.407)
19A325T600-1		600	122.0 (27.5)	13.50 (0.531)
19A325T600-2			134.5 (30.3)	13.00 (0.511)
19A325T600-3			124.0 (27.9)	13.64 (0.536)
19A490T20-1	A490	20	414.0 (93.2)	5.63 (0.221)
19A490T20-2			414.7 (93.3)	7.04 (0.277)
19A490T20-3			429.1 (96.5)	8.09 (0.318)
19A490T200-1		200	412.0 (92.7)	8.33 (0.327)
19A490T200-2			398.0 (89.6)	7.91 (0.311)
19A490T200-3			420.1 (94.5)	8.50 (0.334)
19A490T400-1		400	347.2 (78.1)	10.16 (0.399)
19A490T400-2			354.6 (79.8)	9.37 (0.368)
19A490T400-3			364.5 (82.0)	9.52 (0.374)
19A490T500-1		500	258.0 (58.1)	10.32 (0.406)
19A490T500-2			262.7 (59.1)	10.34 (0.406)
19A490T500-3			258.9 (58.3)	10.40 (0.409)
19A490T600-1		600	158.4 (35.6)	14.03 (0.551)
19A490T600-2			163.7 (36.8)	14.86 (0.584)
19A490T600-3			160.8 (36.2)	15.42 (0.606)

load versus displacement curves for all the experiments. Each figure contains six plots, each for the load versus displacement curves for a specific bolt diameter and steel grade for the individual different testing temperatures: 20 °C, 200 °C, 400 °C, 500 °C, and 600 °C; the last plot shows all load versus displacement together. The variable “Load” plotted in the y-axis represents the total load applied by the universal testing machine to the testing apparatus and, it should be noted that only half of this value is applied to each shear plane in the bolt. The universal testing machine is operated through load control and thus after peak load has been reached the failure is abrupt and the degradation could not be captured.

There is a similar trend in most experiments; a temperature increase leads to a loss of shear strength and to an increase in the shear deformation at failure load, both observations are more pronounced at higher temperatures. At 200 °C, however, the shear strength is similar to that at ambient temperature, but the shear deformation is still higher. The load-displacement curves also have similar characteristics throughout the experiments of 19 mm (3/4 in) and 22 mm (7/8 in) diameter bolts; at lower loads, there is a linear relationship between load and displacement; the load, however, reaches a certain level, second stage, and the displacement increases at a greater rate than the stage before. In a third stage the load and displacement maintain a linear-like relationship with a rate similar to that of the first stage; until, the applied load reaches a level, fourth stage, in which load and displacement does not hold a linear relationship and failure is eminent. For a more thorough discussion on these stages, and their limitations, refer to Weigand et al. [13] in which these relationships are used to develop component-based models for modelling shear behavior in high-strength bolts at elevated temperatures.

3.1. Experimental results – 19 mm (3/4 in) diameter bolt

Figs. 3 and 4, and Table 3 summarize the results presented in this section. Bolts made out of A490 (steel grade) at ambient temperature resists about 10% ± 1.9% (±represents the relative standard error) more shear loading than the A325 bolts. Bolts A325 heated to 200 °C had a slightly higher shear strength by about 2% ± 1.4%, when compared with ambient temperature experiments; A490 bolts, however, had a slightly lower shear strength by about 2% ± 1.6%, when compared with ambient temperature experiments. At 200 °C, however, the temperature influenced the deformation at failure; the A325 bolts' deformation at failure increased by about 12% ± 6.2% compared to the ambient temperature experiments, while the A490 bolts had an increase of about 19% ± 8.7%.

For temperatures between 200 °C and 600 °C, both steel grades had significant degradation in their mechanical properties: shear strength decreased and shear deformation at failure load increased. Shear strength of bolts A325 reduces from about 82% ± 1.3% at 400 °C when compared to experiments at ambient temperature to only 33% ± 1.5% at 600 °C; shear strength of the A490 bolts reduced from about 85% ± 1.4% at 400 °C when compared to experiments at ambient temperature to 38% ± 1.0% at 600 °C. Thus, the shear strength of the A490 bolts degraded slightly less than that of the A325 bolts.

The deformation at failure of the A325 bolts increased from about 42% ± 6.5 %at 400 °C when compared to experiments at ambient temperature to 83% ± 6.5% at 600 °C; deformation at failure of the A490 bolts increased from about 40% ± 8.9% at 400 °C when compared to experiments at ambient temperature to 113% ± 9.7% at 600 °C. Although, the A490 bolts deformation at failure was greater than that of the A325 bolts, note that the failure load was also greater than that of the A325 bolts.

3.2. Experimental results – 22 mm (7/8 in) diameter bolt

Fig. 5, Fig. 6, and Table 4 summarize the results presented in this section. There are many similar observations to what was discussed for the 19 mm (3/4 in) diameter bolts. A490 bolts at ambient temperature resisted about 8% ± 1.1% more shear loading than the A325 bolts (four experiments, instead of the usual three, were carried out at ambient temperature). A325 bolts, when heated to 200 °C, had a reduction in the shear strength of about 4% ± 1.0% compared to ambient temperature experiments; A490 bolts reduced its shear strength by about 5% ± 1.1% when compared to ambient temperature experiments. At 200 °C the deformation at failure load was similar to that of the A325 bolts and it changed by only 1% ± 2.9% when compared to ambient temperature experiments, while A490 bolts showed larger increases by about 11% ± 2.0%, of the deformation at failure. Thus, at 200 °C the shear strength reduction was about the same for both steel grades, but A490 bolts' deformation at failure was more sensitive to increasing temperature.

For temperatures between 200 °C and 600 °C both steel grades, as observed for the 19 mm (3/4 in) bolt diameter, had significant degradation in their mechanical properties: shear strength decreased and shear deformation at failure load increased. Shear strength of A325 bolts reduced from about 85% ± 1.3% at 400 °C when compared to experiments at ambient temperature to only 33% ± 1.0% at 600 °C; shear strength of the A490 bolts reduced from about 81% ± 1.5% at 400 °C when compared to experiments at ambient temperature to 37% ± 1.1% at 600 °C. Thus, the A490 bolts shear strength degraded slightly less than that of the A325 bolts.

Deformation at failure of the A325 bolts increased from about 27% ± 3.1% at 400 °C when compared to experiments at ambient temperature to 51% ± 4.6% at 600 °C; deformation at failure of the A490 bolts increased from about 34% ± 3.3% at 400 °C when compared to experiments at ambient temperature to 95% ± 4.7% at 600 °C.

3.3. Experimental results – 25 mm (1 in) diameter bolt

Fig. 7, Fig. 8, and Table 5 summarize the results presented in this section. A490 bolts at ambient temperature resisted to about

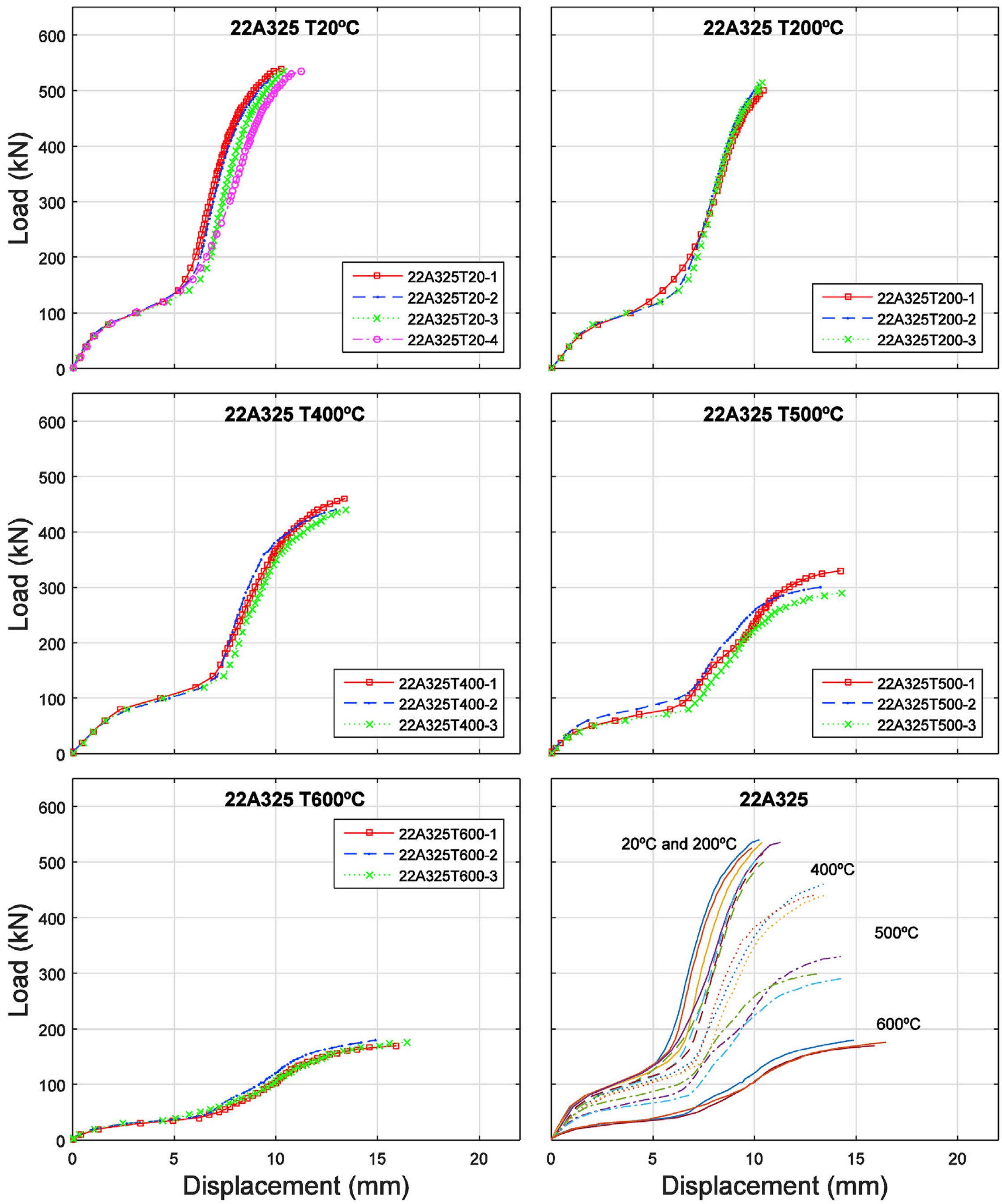

Fig. 5. Load versus displacement for the 22 mm (7/8 in) A325 bolts.

13% ± 0.4% more shear loading than the A325 bolts. A325 bolts when heated to 200 °C showed a reduction in the shear strength of about 4% ± 0.7% when compared to ambient temperature experiments; A490 bolts, however, had a slightly lower shear strength, about 2% ± 0.3%, when compared to ambient temperature experiments. At 200 °C, however, A325 bolts' deformation at failure had a decrease of 11% ± 7.8% when compared to ambient temperature experiments, while A490 bolts had an increase of about 16% ± 5.5%. Thus, although shear strength considerably changed for the A325 bolts, shear deformation slightly decreased; conversely, A490 bolts shear strength is about the same, while shear deformation was considerably higher.

For temperatures between 200 °C and 600 °C, as showed for the 19 mm (3/4 in) and the 22 mm (7/8 in) bolts, both steel grades had significant degradation in their mechanical properties: shear strength decreased and shear deformation at failure load increased. Shear strength of the A325 bolts reduced from about 79% ± 0.7% at 400 °C when compared to experiments at ambient temperature to about 33% ± 0.6% at 600 °C; shear strength of the A490 bolts reduced from about 81% ± 0.6% at 400 °C when compared to experiments at ambient temperature to only 39% ± 1.3% at 600 °C. A490 bolts, however, were abruptly affected by raising the temperature from 500 °C to 600 °C, while at 500 °C the shear strength reduction was about 60% ± 0.3%, at 600 °C the shear strength reduced to about 39% ± 1.3% when compared to experiments at ambient temperature. The next section will discuss this observation in more detail.

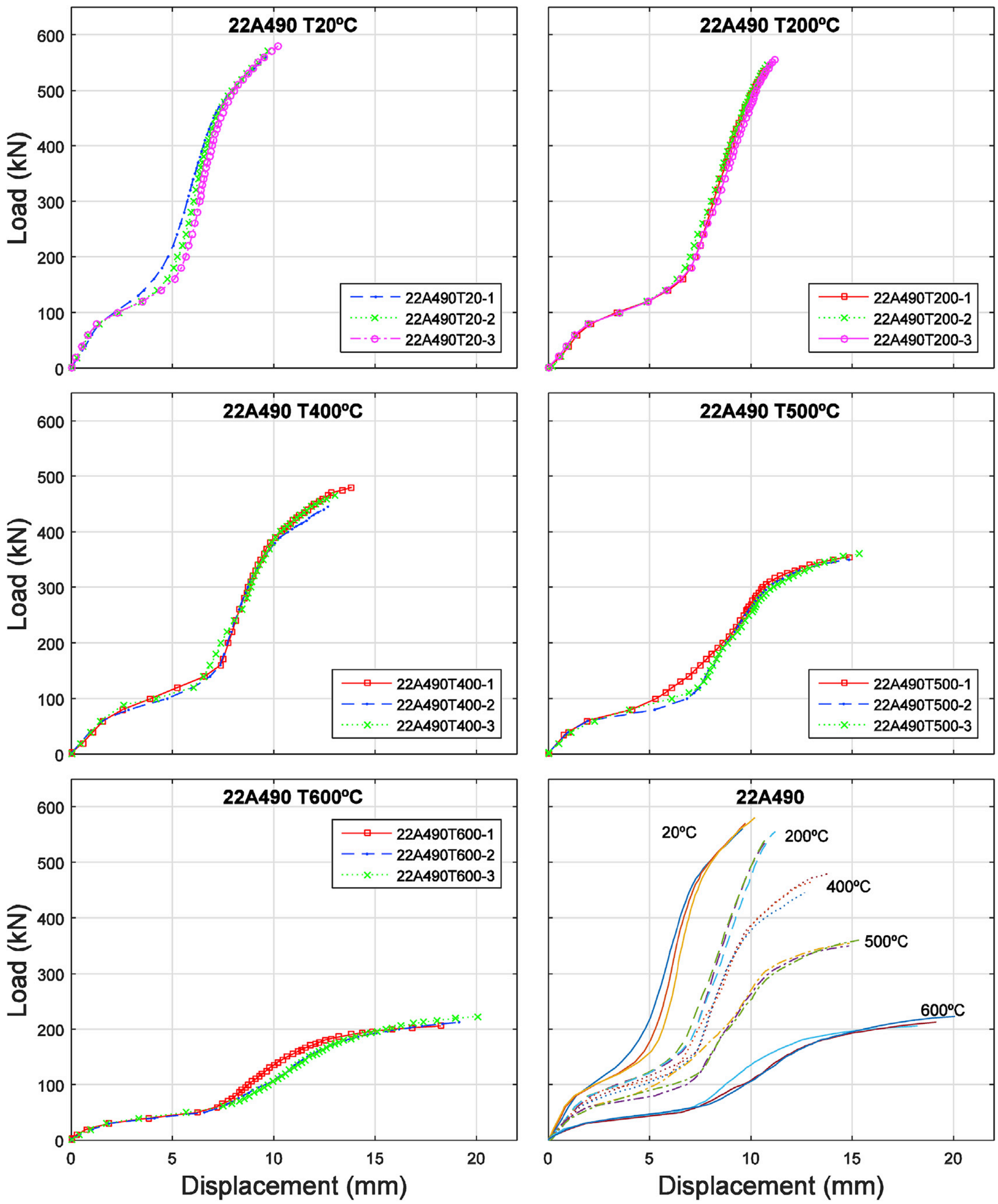

Fig. 6. Load versus displacement for the 22 mm (7/8 in) A490 bolts.

Deformation at failure of the A325 bolts increased from about 43% ± 12.1% at 400 °C when compared to experiments at ambient temperature to about 76% ± 9.3% at 600 °C; deformation at failure of the A490 bolts increased from about 44% ± 7.6% at 400 °C when compared to experiments at ambient temperature to about 250% ± 19.9% at 600 °C. As discussed in the following section, it is not possible to directly compare displacement values at failure measured for the 25 mm (1 in) bolts to those for the 19 mm (3/4 in) and 22 mm (7/8 in) bolts, since the material of the loading blocks was changed.

4. Discussion

4.1. Testing blocks

As mentioned before, two sets of testing blocks were designed to carry out the experiments; the design aimed to develop blocks that would withstand the loading with minimal deformation compared to the bolt deformation. For the 19 mm (3/4 in) and 22 mm (7/8 in) bolt diameter tests, the same set of testing blocks was used and only the hole necessary to pass the bolt was enlarged after all the 19 mm (3/4 in) bolts were tested. For the 25 mm (1 in) bolts diameter tests, a new testing block with same dimensions was manufactured, using a different steel grade: AISI/SAE 8640 thermal treated instead of ASTM A36.

This change of material affected the configuration of the loading versus displacement curve. For the 19 mm (3/4 in) and 22 mm (7/8 in) bolt diameter tests, the loading versus displacement curve, after a short first stage, it presents a second stage in which the displacement increases at a greater rate than before; this second stage is nonexistent in all 25 mm (1 in) bolts' experiments. This second stage is due to

Table 4
Results for 22 mm (7/8 in) bolt diameter experiments.

Specimen Name	Steel	Temperature (°C)	Failure Load (kN)	Displacement at Failure (mm)
22A325T20-1	A325	20	540.0 (121.5)	10.24 (0.402)
22A325T20-2			527.6 (118.7)	9.86 (0.388)
22A325T20-3			539.9 (121.5)	10.38 (0.408)
22A325T20-4			523.0 (117.7)	11.27 (0.443)
22A325T200-1		200	503.0 (113.2)	10.43 (0.400)
22A325T200-2			513.8 (115.6)	10.21 (0.401)
22A325T200-3			517.2 (116.4)	10.41 (0.409)
22A325T400-1		400	464.0 (104.4)	13.41 (0.500)
22A325T400-2			442.5 (99.6)	12.94 (0.500)
22A325T400-3			444.1 (99.9)	13.48 (0.530)
22A325T500-1		500	332.3 (74.8)	14.25 (0.560)
22A325T500-2			304.2 (68.4)	13.26 (0.521)
22A325T500-3			294.3 (66.2)	14.30 (0.562)
22A325T600-1		600	171.8 (38.7)	15.92 (0.626)
22A325T600-2			182.8 (41.1)	14.89 (0.585)
22A325T600-3			178.9 (40.3)	16.47 (0.647)
22A490T20-1	A490	20	568.0 (127.8)	9.59 (0.377)
22A490T20-2			574.8 (129.3)	9.72 (0.382)
22A490T20-3			587.7 (132.2)	10.20 (0.401)
22A490T200-1		200	537.2 (120.9)	10.69 (0.420)
22A490T200-2			548.7 (123.5)	10.80 (0.424)
22A490T200-3			555.2 (124.9)	11.19 (0.440)
22A490T400-1		400	480.3 (108.1)	13.85 (0.544)
22A490T400-2			449.9 (101.2)	12.65 (0.497)
22A490T400-3			466.3 (104.9)	13.04 (0.512)
22A490T500-1		500	356.8 (80.3)	14.86 (0.584)
22A490T500-2			352.6 (79.3)	14.84 (0.583)
22A490T500-3			362.7 (81.6)	15.33 (0.602)
22A490T600-1		600	206.4 (46.4)	18.23 (0.716)
22A490T600-2			214.5 (48.3)	19.14 (0.752)
22A490T600-3			224.0 (50.4)	20.07 (0.789)

localized deformation at the bolt hole, which was confirmed by measurements taken of the bolt-hole diameter throughout the study; for 19 mm (3/4 in) and 22 mm (7/8 in) bolt diameter the bolt hole slightly increases after each experiment, but for 25 mm (1 in) bolts the bolt hole practically does not change except for the 600 °C. Thus, if these experiments are to be modeled, proper consideration of the incremental change of the bolt-hole diameter after each experiment is essential. It is noted that although the testing block's deformation affects the overall deformation of the 19 mm (3/4 in) and 22 mm (7/8 in) diameter bolts, it has no effect on their strength (capacity). Their test results provide very reliable data for the purpose of characterizing the degradation in bolts' strength and developing retention (reduction) factors at different temperatures. The unaffected results of the 25 mm (1 in) diameter bolts will provide further information needed for the development of full models. For a detailed discussion on the different stages of the loading versus displacement curve, refer to Weigand et al. [13] in which these relationships are used to develop an empirical component-based model for modelling shear behavior in high-strength bolts at elevated temperatures. .

4.2. Shear strength

The bolt shear strength is directly proportional to the cross-section area of the bolt shaft. The ratio between the area of a 25 mm (1 in) diameter bolt and a 19 mm (3/4 in) is 1.73, while the ratio between the area of a 22 mm (7/8 in) diameter bolt and a 19 mm (3/4 in) is 1.34. A comparison between the shear strength of bolts with A325 steel grade is shown in Fig. 9, while Fig. 10 shows the same comparison for bolts with A490 steel grade. Note that, for any temperature, and both materials, the area ratio is similar to the ratio between failure loads.

Figs. 9 and 10 also show that, for all diameters and materials tested herein, the shear strength was nearly constant up to 200 °C. From 200 °C to 400 °C there is a clear shear strength reduction, which increased at an increasing rate from 400 °C to 600 °C; note that from 400 °C to 600 °C the degradation of shear strength is nearly linear.

Fig. 11 shows the shear strength retention by the ratio of the failure load of a certain experiment by the average shear strength at ambient temperature for the same bolt diameter and material. The shear strength retention consistently changes at similar rate for the two materials and three bolt diameters.

Fig. 12 shows how the double-shear retention factors from the experimental results compare to the to the design retention factors specified in the Eurocode [14], as well as to the other experimental results found in the literature; particularly from Kodur [6], and Yu [7]. Per the Eurocode, the fire design resistance of bolts loaded in shear should be determined from:

$$F_{v,t,Rd} = F_{v,Rd}\, k_{b,\theta} \frac{\gamma_{M2}}{\gamma_{M,fi}} \tag{1}$$

where $k_{b,\theta}$ is the reduction factor determined at the appropriate temperature (Table D1 of [14]).

$F_{v,Rd}$ is the design shear resistance of the bolt per shear plane (Annex D of [14]),
γ_{M2} is the partial factor at normal temperature, and
$\gamma_{M,fi}$ is the partial factor for fire conditions.

The retention factors were relatively consistent across all three bolt diameters and for both bolt material grades. For temperatures up to 500 °C, the Eurocode retention factors were 5%–10% more conservative than the experimental data. However, at 600 °C, the Eurocode was about 40% more conservative than the experimental data. It is

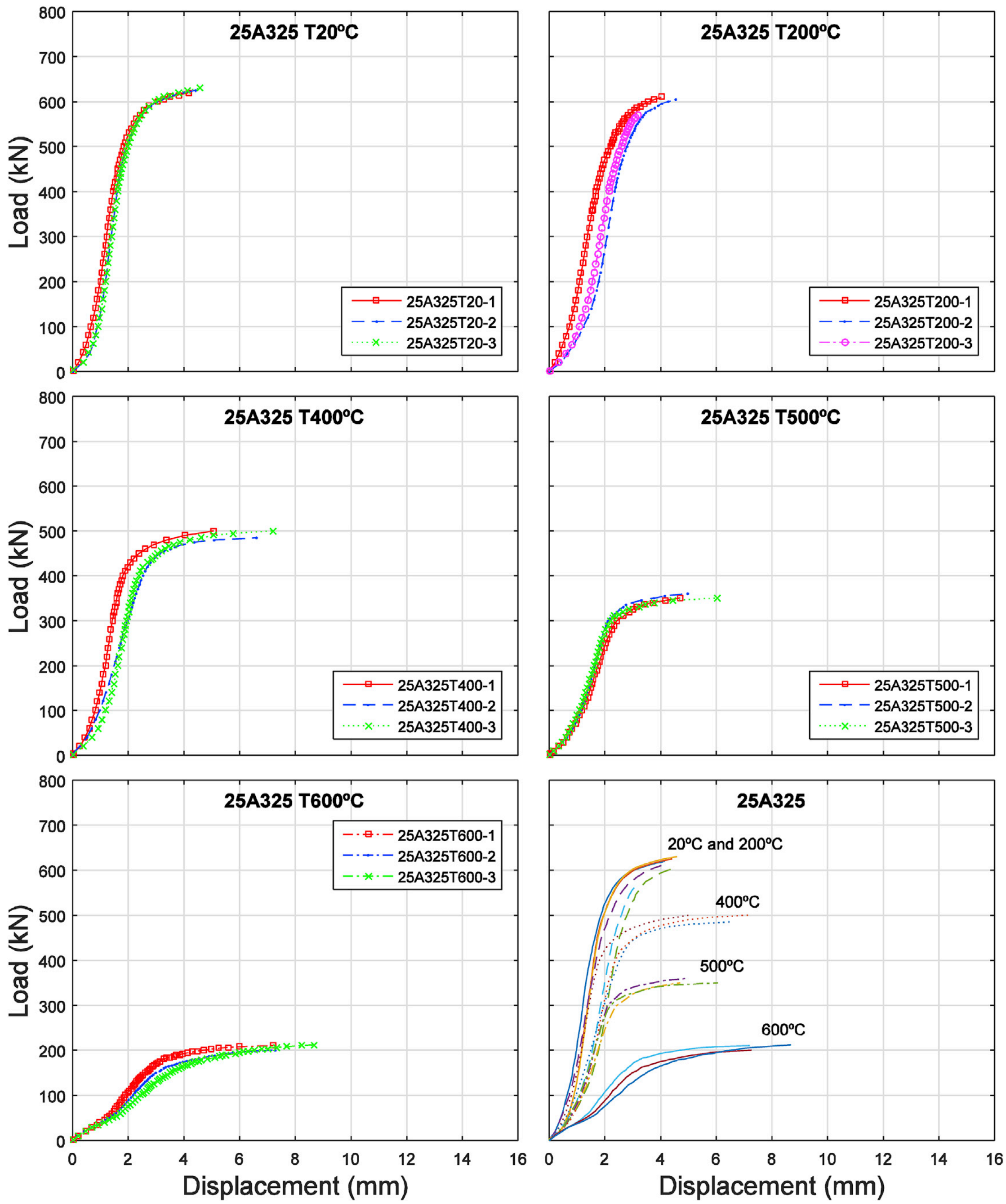

Fig. 7. Load versus displacement for the 25 mm (1 in) A325 bolts.

noted that data from Kodur [6], as well as from Yu [7], is limited to one result at each tested temperature, and the studies' scope was limited to one bolt diameter (22 mm (7/8 in)), making any full comparison inconclusive. Finally, it is noted that the AISC [15] does not specify retention factors values for high-strength bolts at elevated temperatures.

4.3. Displacement at failure load

The loading blocks used for the 25 mm (1 in) bolt diameter tests is different than the blocks used for the 19 mm (3/4 in) and 22 mm (7/8 in) bolt diameter tests, which is discussed in more detail in the next section; also, deformation at failure load must be always taken in account together with shear strength or steel grade, for example: A490 bolts have consistently presented for experiments at 600 °C greater deformation at failure load when compared to A325 bolts, but it does not necessarily mean that A490 bolts are less stiff than A325 bolts at 600 °C. On the other hand, since the average deformations at failure load from ambient temperature through 500 °C are similar when comparing different steel grades and same bolt diameter, it is concluded that A490 bolts are stiffer than A325 bolts since it has greater shear strength but similar shear deformation. Fig. 13 shows the displacement at failure at different temperatures for different bolt diameters and bolt grades.

4.4. Bolt curvature after testing

Although this paper aims to only study the shear behavior of steel bolts, a small amount of bending is intrinsic in any experiment. To address and document this issue, after each bolt was tested, an image

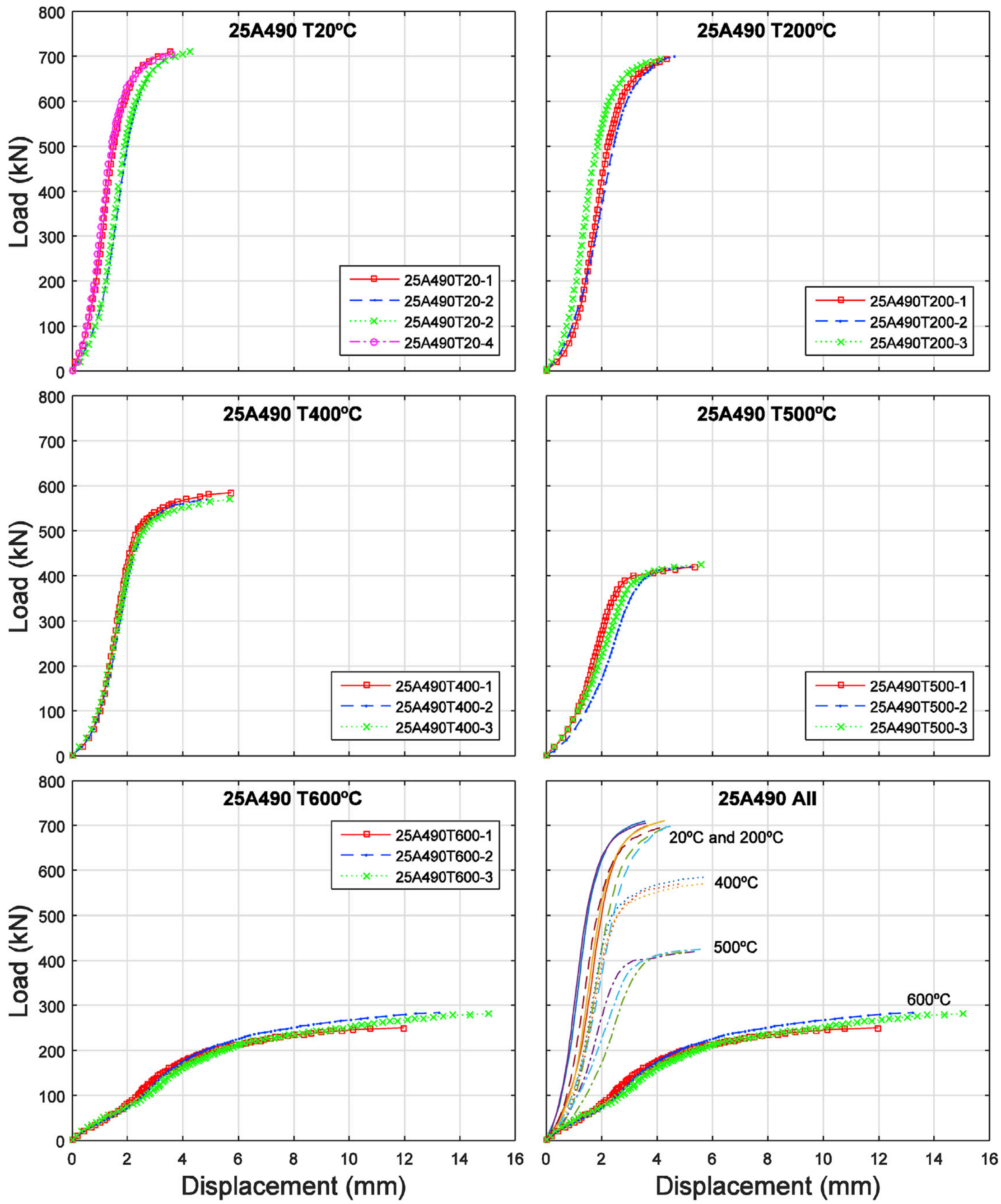

Fig. 8. Load versus displacement for the 25 mm (1 in) A490 bolts.

scanning was carried out, measuring the curvature of the bolt centerpiece located between both shear planes, as shown in Fig. 14.

Fig. 15 shows the increase in the final bolt curvature with the progression of the study for the different bolt sizes. The 19 mm (3/4 in) and 22 mm (7/8 in) diameter bolts had greater amounts of bending deformation after testing, and greater curvature, when compared to the 25 mm (1 in) diameter bolts; such observation is due to the fact that the testing blocks for the 25 mm (1 in) diameter bolts, which had higher strength and stiffness, allowed less local deformation which led to less bending. Also, the testing sequence due to the incremental bolt-hole deformation and increase in the testing temperature led to increased amounts of bending. Nonetheless, the amount of bending deformation was still small compared to the amount of shear deformation.

4.5. *Shear plane fracture*

Fig. 16 shows, pictures of the shear plane fracture of one bolt sample at each temperature; in this figure becomes clear: (i) the type of failure, varying from a clearer cut surface to a more viscous type of shear failure, and (ii) the change of coloration, varying from a clear silver color, to a blue coloration, and finally to a black coloration.

For ambient temperature, the shear plane is brilliant, silver/grey color, smooth but not necessarily flat. Some shear planes present waves/undulations. The shear plane for 200 °C is very similar to that of the ambient temperature: brilliant, silver/grey color, little less smooth with some groove marks on the bottom. For both ambient temperature and 200 °C, a slight plastic deformation is visible, due to the vertical bolt displacement during the loading.

Table 5
Results for 25 mm (1 in) bolt diameter experiments.

Specimen Name	Steel	Temperature (°C)	Failure Load kN (kip)	Displacement at Failure mm (in)
25A325T20-1	A325	20	623.6 (140.3)	4.15 (0.163)
25A325T20-2			629.2 (141.6)	4.41 (0.173)
25A325T20-3			631.3 (142.0)	4.59 (0.180)
25A325T200-1		200	612.1 (137.7)	4.02 (0.158)
25A325T200-2			607.2 (136.6)	4.54 (0.178)
25A325T200-3			596.5 (131.2)	3.17 (0.125)
25A325T400-1		400	500.6 (112.6)	5.05 (0.199)
25A325T400-2			485.4 (109.2)	6.60 (0.259)
25A325T400-3			500.6 (112.6)	7.18 (0.282)
25A325T500-1		500	354.9 (79.9)	4.70 (0.185)
25A325T500-2			361.3 (81.3)	4.98 (0.196)
25A325T500-3			350.1 (78.8)	6.06 (0.238)
25A325T600-1		600	210.7 (47.4)	7.20 (0.283)
25A325T600-2			200.7 (45.2)	7.27 (0.286)
25A325T600-3			212.1 (47.7)	8.68 (0.341)
25A490T20-1	A490	20	710.3 (159.8)	3.56 (0.140)
25A490T20-2			704.5 (158.5)	3.65 (0.144)
25A490T20-3			713.6 (160.6)	4.27 (0.168)
25A490T20-4			707.6 (159.2)	3.59 (0.141)
25A490T200-1		200	696.2 (156.6)	4.34 (0.170)
25A490T200-2			700.0 (157.5)	4.63 (0.182)
25A490T200-3			698.4 (157.1)	4.13 (0.162)
25A490T400-1		400	585.4 (131.7)	5.73 (0.225)
25A490T400-2			573.0 (128.9)	4.86 (0.191)
25A490T400-3			570.0 (128.3)	5.70 (0.224)
25A490T500-1		500	423.3 (95.2)	5.35 (0.210)
25A490T500-2			424.4 (95.5)	5.20 (0.204)
25A490T500-3			425.3 (95.7)	5.58 (0.219)
25A490T600-1		600	251.8 (56.7)	11.97 (0.470)
25A490T600-2			285.7 (64.6)	13.23 (0.520)
25A490T600-3			283.6 (63.8)	15.06 (0.592)

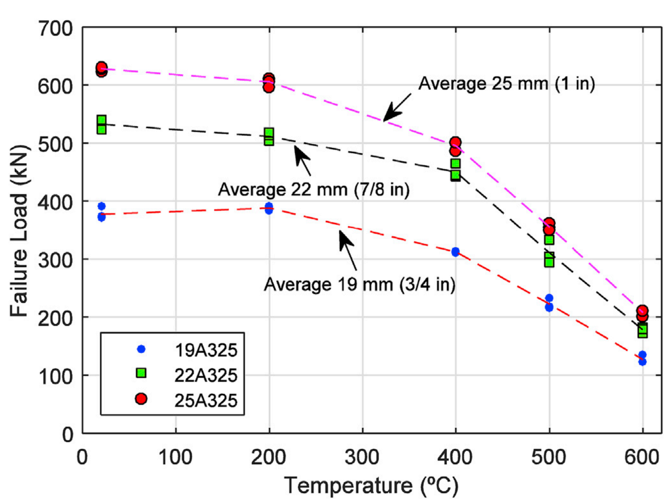

Fig. 9. Failure load versus temperature for the A325 bolts.

At 400 °C, the shear surface is rough and with parallel abrasion marks, indicating the increase in steel ductility. Also, the color becomes blue, due to the steel oxidation at this temperature. For 500 °C, the shear plane shows larger parallel abrasions compared to 400 °C. The color is not blue anymore, but it's still rough. At 600 °C, the shear plane shows a red/copper color and the entire surface is flat. The parallel abrasion marks are visible, however, they are softer, and a rough part extends along the entire bolt end, as the material starts to enter a major phase change at this temperature.

The shear planes of the 25 mm (1 in) diameter bolts are flatter than those of the 19 mm (3/4 in) and 22 mm (7/8 in) diameter bolts, though for ambient temperature and 200 °C, the shear plane showed a kink on the surface. This is presumably, due using a different block set: the one used for the 25 mm (1 in) diameter tests did not have bolt hole

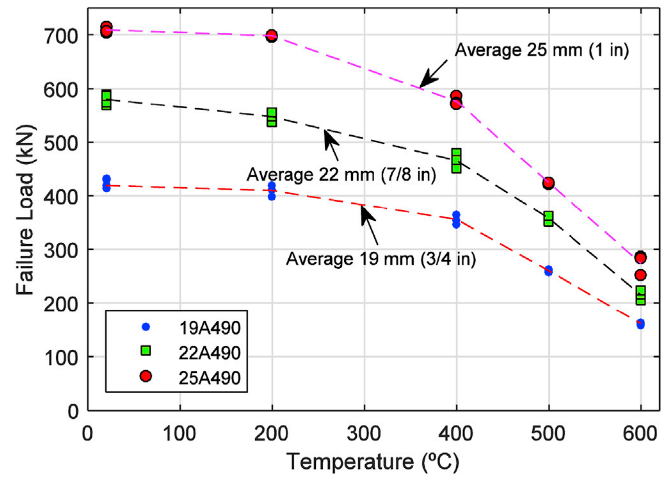

Fig. 10. Failure load versus temperature for the A490 bolts.

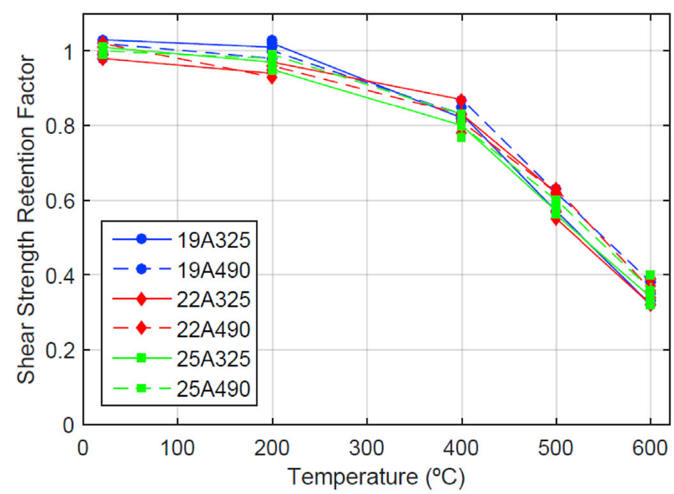

Fig. 11. Shear strength retention factor versus temperature.

deformation.

5. Ongoing work

It is noted that the main scope of this paper is to present the results of the experimental study, along with all the details of the specimens and test setup, that allow the repeatability of the study. Other work is either currently underway or has been completed that interprets and utilizes the data presented herein. For example, Seif et al. [16] compares the results to the Eurocode 3 [14]. Other submitted articles present the development of temperature-dependent material models for high-strength bolts, and the development of reduced-order modelling approaches for high-strength bolts under shear loads at elevated temperatures, based on the experimental results [13].

6. Summary and conclusions

This paper presented results from recently conducted tests on high-strength structural bolts subject to double shear loading at elevated temperatures. The parameters varied between tests included the bolt grade, bolt diameter, and temperature. Bolt grades A325 and A490 were tested. For each bolt grade, three different diameters were tested (19 mm (3/4 in), 22 mm (7/8 in), and 25.4 mm (1 in)) at five different temperatures (20 °C, 200 °C, 400 °C, 500 °C, and 600 °C). At least three tests were conducted for each combination of parameters. Degradations in the

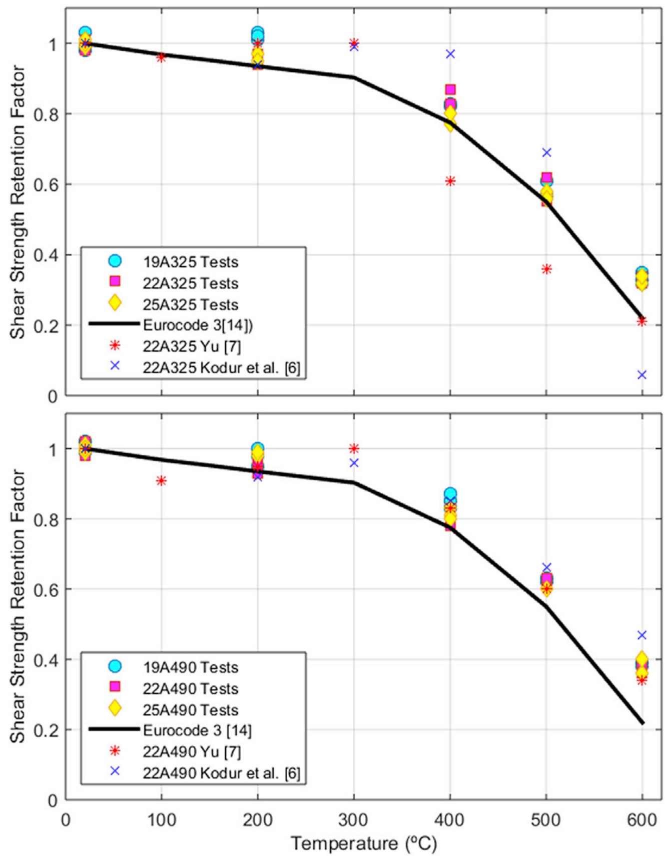

Fig. 12. Comparison of different shear strength retention factors for (a) A325 bolts, and (b) A490 bolts.

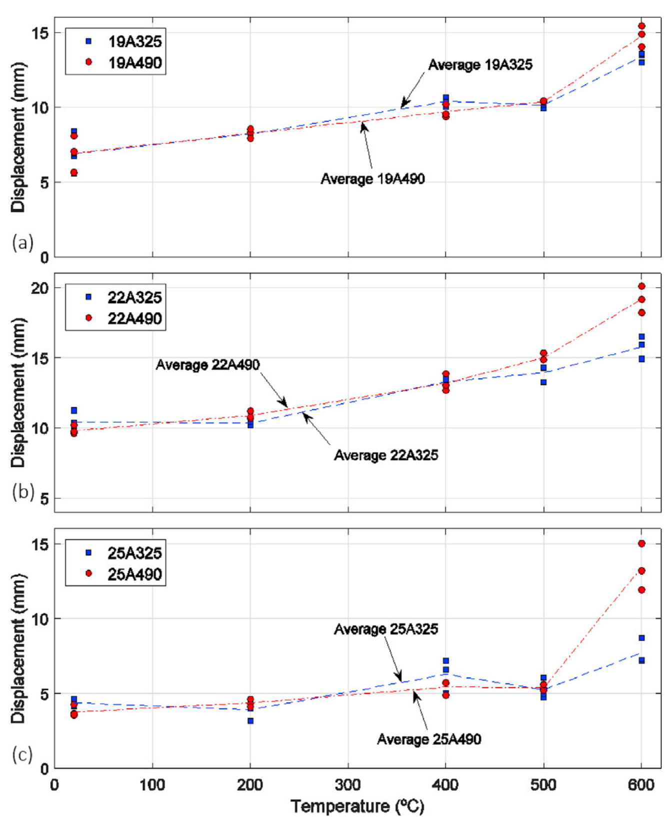

Fig. 13. Displacement at failure versus temperature for: (a) 19 mm (3/4 in) bolts, (b) 22 mm (7/8 in) bolts, and (c) 25 mm (1 in) bolts. (1 in = 24.5 mm).

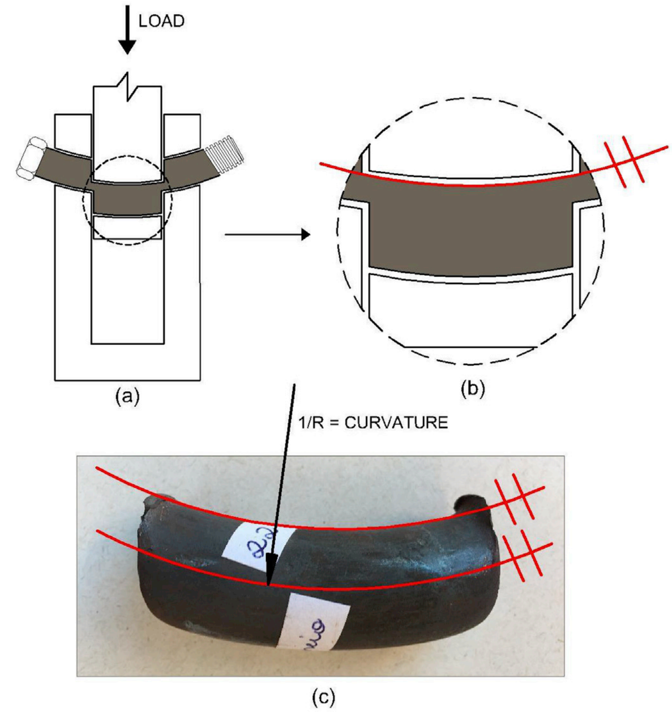

Fig. 14. Curvature: (a) amplified deformed shape before complete bolt shear failure, (b) zoom in the bolt, and (c) photo showing bolt's curvature after testing.

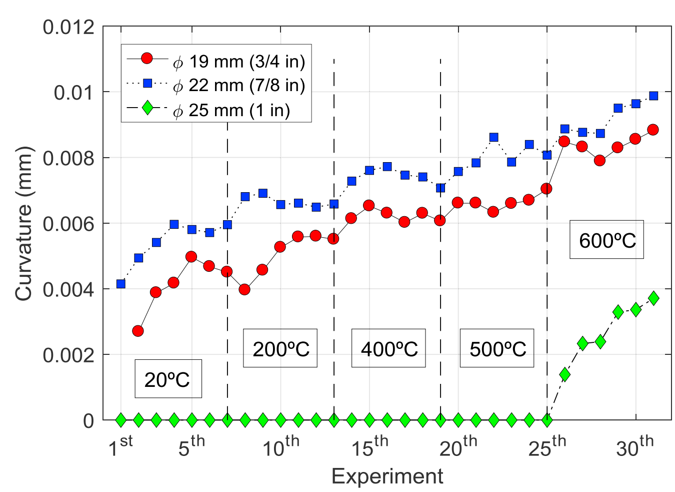

Fig. 15. Curvature versus order of each experiment in the sequence of experiments. (1 in = 24.5 mm).

mechanical and material properties including stiffness, strength, and deformation at fracture, were characterized and presented herein. The results from these experiments fill a critical knowledge gap currently present in the literature regarding the behavior of high-strength structural bolts under shear loading at elevated temperatures.

Results showed that up to 200 °C, the bolts do not lose their shear strength if compared to ambient temperature, however, the deformation is higher. As the temperature increases, the shear strength gradually decreases. Under 400 °C, the bolts held approximately 82% of their initial strength. At 500 °C, the A325 and A490 bolts both held about 60% of the initial shear strength. At 600 °C, the bolts were down to about 35% of their initial resistance. Development of temperature-dependent material models for high-strength bolts that capture the behavior observed in this study is currently underway.

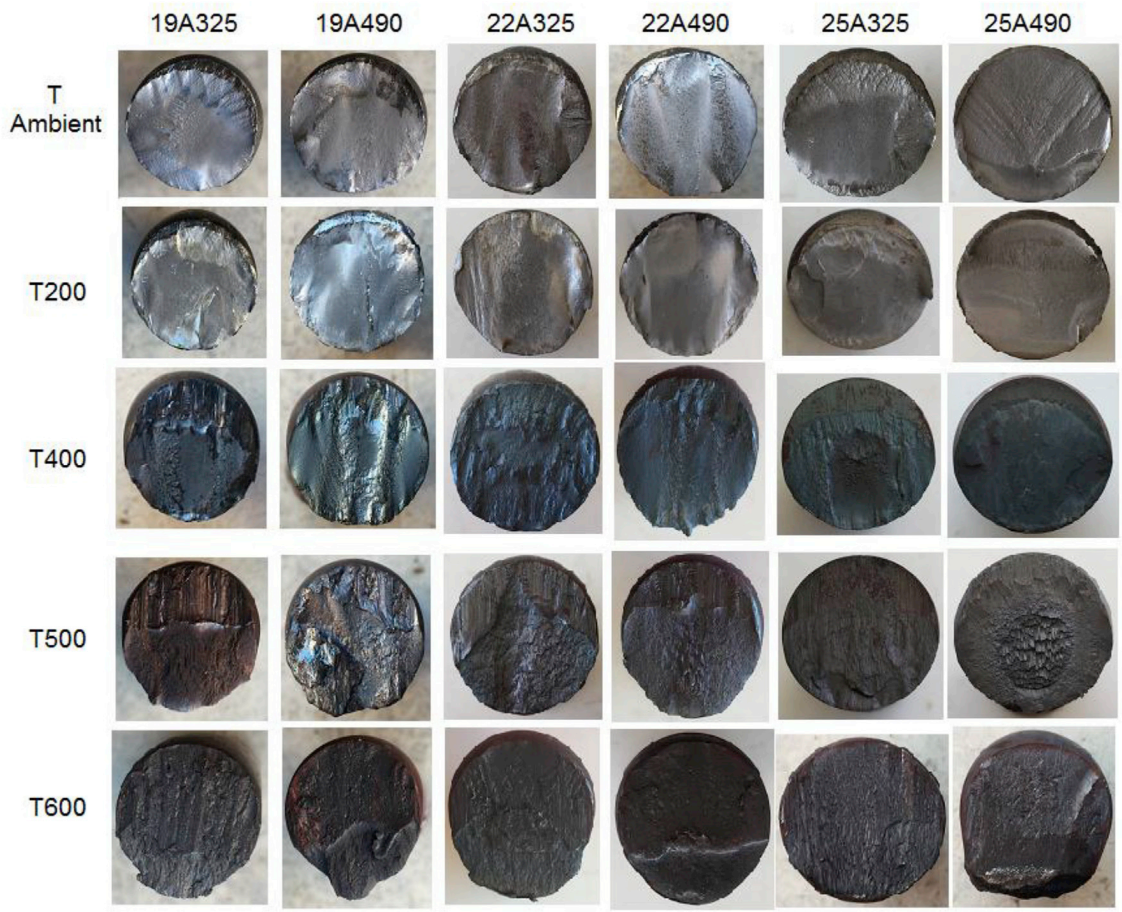

Fig. 16. Pictures of bolts shear plane.

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