

Behavior of ASTM A325 bolts under simulated fire conditions: experimental investigation

ASTM A325
bolts

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Abstract

Purpose – Heavy hex structural bolts have been used in a wide range of steel structures for many years. However, these structures remain susceptible to fire damage. Conducting fire experiments on full-scale steel structures is costly and requires specialized equipment. The main purpose of this research is to test, analyze and predict the behavior of ASTM A325 bolts under tension loading in simulated fire conditions and develop a reliable finite element model that can predict the response of similar bolts without the need for repeated testing.

Design/methodology/approach – The experimental work was conducted at the University of Wisconsin-Milwaukee, where an electric furnace was custom-built to test a bolted specimen in tension under elevated temperatures. A transient-state testing method was adopted to perform a group of tests on 12.7 mm ($\frac{1}{2}$ " – diameter A325 bolts. The tests were divided into two groups: the first one was used to calibrate the equipment and choose a final testing arrangement and the second group, consisting of four identical tests, was used to validate a finite element model.

Findings – The temperature-displacement and load-displacement response was recorded. The tested bolts exhibited a ductile fracture in which a cup-and-cone shaped failure surface was formed in the threaded section at the root of the nut. ASTM A325 bolts are widely used by engineers in building and bridge construction, the results of this research enable engineers to determine the behavior and strength of ASTM A325 bolts when such bolts when exposed to fire event.

Research limitations/implications – Structural bolts are used to connect structural members, and they are part of structural assembly. To study the behavior of the bolts, the bolts only were investigated in a fire simulated in a furnace. The bolts studied were not part of a structural assembly.

Practical implications – The results of this study enable engineers to evaluate the condition of ASTM A325 bolts when subjected to fire loading.

Originality value – Tests were conducted at the University of Wisconsin – Milwaukee's structures laboratory to study the effect of fire on an ASTM A325 bolts. Many tests under fire loading have been performed by researchers on different components of steel structures, this study focuses on studying the behavior of ASTM A325 bolts which are widely used in the USA.

Keywords Steel, A325 bolts, Elevated temperature, Finite element analysis

Paper type Research paper



1. Introduction

Steel structures have become widely used since the dawn of the twentieth century, owing to the benefits of steel as a relatively lightweight material with high strengths

and low cost. Yet, steel structures are still vulnerable to fatigue, corrosion and fire damages. This paper presents an experimental investigation into the heat-induced degradation of steel bolts under simulated fire conditions. To develop a better understanding of the behavior of structural bolts during a fire, ASTM A325 bolts were heated until failure under constant tension loading. Tension-loaded bolts were chosen because they are common in moment-resisting connections and more susceptible to failure than those located on the compressed side of the connection.

Applying a heat gradient to a single component, like a bolt may not be used to assess the integrity of the structure as a whole. However, it certainly helps in understanding the response of this component and sheds the light on its role in the initiation and progression of failure during a fire event and that is one of the main objectives of these experiments. The onset of bolt failure in a connection can lead to an overall failure of the joint.

In addition to the experimental work presented in this research, a finite element model has also been developed in an effort to emulate the results of the experimental work and make it easier to replicate the experiments on a wider array of bolts than the one used.

2. Literature review

In recent years, finite element software packages such as ABAQUS, ANSYS, Simulation Mechanical and SAP2000 have grown more powerful than ever, offering the engineering professional a relatively cheap and reliable tool to solve a wide range of problems in an efficient and accurate manner. In particular, finite element modeling has been used by the automotive, aircraft and heavy machinery industries to model extreme conditions that otherwise require expensive testing rigs and specially equipped facilities.

The behavior of steel members under elevated temperatures is one example of the extreme conditions where finite element analysis (FEA) could be utilized. A finite element model of the member in question could be built and verified against experimental data, then used repeatedly thereafter to analyze similar cases.

In the early 1990s, [Bose *et al.* \(1991\)](#) made an attempt to investigate the response of a steel connection making use of FEA to study the behavior of welded beam-to-column connections by considering strain hardening, buckling and material plasticity in the analysis. The obtained results compared closely with the available experimental data.

Krishnamurthy developed a sophisticated finite element model of steel connections that takes into account the bolt preloading and considers the support of the end-plate as rigid. The close correlation between the numerical results and experimental data demonstrated the importance of including the bolt heads and welds in the numerical models to accurately define the connection response. Based on the work conducted by [Krishnamurthy \(1980\)](#), [Murray and Kukreti, \(1988\)](#) studied the behavior of flush end-plate connection and eight types of extended end-plate arrangements. [Al-Jabri *et al.* \(2005\)](#) developed a three-dimensional (3D) finite element model using ABAQUS, in which he studied the behavior of a group of flush-end plate connections under elevated temperatures with good agreement to some experimental results of the same connections he conducted as part of his PhD dissertation. The experimental work developed extensive data about the moment-temperature-rotation response of bare steel flush-end plate connections.

Recently, a detailed 3D nonlinear FE model was developed by [Rahman *et al.* \(2007\)](#) and [Mahamid *et al.* \(2007\)](#) to study shear tab steel connections. This study was published by the American Institute of Steel Construction. Mahamid modeled the shear tab connection at ambient temperature and calibrated his results through experimental testing. The

results of the FE model showed close agreement to test data and is useful in building similar future models.

Yu *et al.* (2009) studied experimentally shear behavior of ASTM A325 and A490 bolts in fire and post-fire conditions. An electric furnace was used to heat a specimen of two bolts (7/8" diameter) under double shear, whereas a digital video camera was used to take real-time images through an observation port. The deformations were determined based on the digital imagery using a software. The temperature of the tested bolts was kept constant during all tests while the shear load increased until failure; this was repeated for different temperatures (from 25 to 800°C in 100°C increments). As a result, shear strength reduction factors for A325 and A490 bolts during fire were obtained from the tests. It was also found that the residual shear strength of the bolts after heating would be reduced by 40-45 per cent.

Kirby (1995) performed elevated temperature component testing on high-strength Grade 8.8 bolts under tension and double shear. The experiments performed highlighted the conservative nature of the guidelines used at the time based on designing at the Fire Limit State, BS5950: Part 8. Also, post-fire evaluation of the tested bolts showed the effect of high temperatures on the residual hardness of high-strength bolts and a procedure to estimate the maximum temperature bolts may have been exposed to during a fire.

Yang *et al.* (2011) investigated the failure of bolted connections under shear loading and temperatures up to 650°C. Based on the results of the experiments, it was concluded that the AIJ specification provides a conservative prediction for the bolts strength, whereas the BS5950 was on the conservative side similarly to the findings of Kirby (1995).

Lange and González (2012) of the Technische Universität Darmstadt have experimentally validated the reduction factors for grade 10.9 bolts given in the Eurocode. The stress-strain and reduction factors curves were verified and the results showed close agreement with the given graphs in the Eurocode.

Rahman *et al.* (2007) used ANSYS to study the moment-rotation-temperature response of flush end-plate bare steel connections. These connections were part of a group of connections tested experimentally by Al-Jabri (1999) at the University of Sheffield in the UK and the finite element model results were in a very close agreement with experimental results. The finite element model utilized 3D solid elements analyzed thermally and statically.

Mao *et al.* (2009) did experimental and 3D finite element study of the fire response of steel semi-rigid beam-column moment connections. The experimental work for this study was performed in the fire laboratory center of the Architecture and Building Research Institute in Taiwan. A single cantilever w-beam attached to a vertical column was tested multiple times under two different loading conditions. The first type of loading was done by applying a constant transverse loading on the beam with increasing temperature, whereas in the second type, the temperature was constant with increasing transverse loading. The numerical model, developed using ANSYS, was in a very close agreement with the experimental results.

Rahman *et al.* (2007) also used ANSYS to study the behavior of fin-plate connections in fire. Four types of element were used in the modeling of beams, column, fin-plate and bolts. These elements were two types of 3D solid elements, pre-tensioning elements and contact elements. An eight-node solid brick element was used to model the entire structure, and a tetrahedral element with curved edges was used to model the bolts. Despite realistic results being predicted by the model, no experimental data were used to investigate its accuracy.

Kodur *et al.* (2012) investigated the effects of high temperatures on the mechanical and thermal properties of A325 and A490 steel bolts. Unlike the study presented in this paper, Kodur chose to perform steady-state tests on machined bolts where the fractured surface always occurred in the shank. The results of these tests showed that the A490 steel has slightly lower thermal conductivity than the A325 steel. In addition, changes in temperature

will not have a significant effect on yield and ultimate strengths until after 400°C. At 700°C only 5 per cent of the ambient-temperature strength will remain.

4. Fire in small compartments and standard fires

The space in a building is usually divided into smaller “compartments” which, depending on the function of the building, may serve as bedrooms, kitchens or offices. If a fire breaks out, these compartments, with proper insulation, can also be used to prevent the spread of fire between the different compartments of the building. This type of fire is called a “compartment fire”, which in fire safety design is easier to handle than unrestricted fires in large open spaces. Older structures with smaller divisions provide a perfect example of the compartment fire behavior where a uniform distribution of design fires can be used in structural design. However, that is not the case in many of the new building-designs, where large open spaces are commonplace and the behavior of fire would not be restricted to a small compartment.

In a small compartment fire, a fire starting in a corner of a room would spread rapidly in what is known as “flashover” provided that an adequate supply of air and fuel (any combustibles in the room) is available. During a flashover, the fire would spread away from its origin when the upper level of hot gases trapped in the room under the ceiling builds up enough heat to convey downward through radiation and convection to any fuel on the lower levels of the room. When the combustible material reaches the ignition temperature, it will ignite and fire will engulf the whole room.

Different nominal or standard fire curves have been developed for use during the design process of structures subject to fire conditions. The choice of using a certain fire curve over the other is largely dependent on the nature of the structural element being considered. [Figure 1](#) shows a comparison between three standard fire curves.

5. Test setup and specimen design

5.1 Specimen components and general description

The tested specimen consisted of a single ASTM A325 structural bolt [12.7 mm ($\frac{1}{2}$ ”) in diameter]. The bolt connected two square 101.6 mm \times 101.6 mm (4” \times 4”) hollow structural steel sections, which were in turn attached to a tension-testing machine grips through two vertical [25.4 mm (1”) in diameter] bars as shown in [Figure 2\(a\)](#). In some of the experiments, a high-temperature strain gage was fitted to the shank of the tested bolt as shown in [Figure 2\(b\)](#). To accommodate this strain gage, a spacer piece of steel is placed in between the two hollow steel sections. The steel bolt and the two steel sections along with a small part of the two vertical bars were enclosed into a custom-built furnace. The dimensional properties of the bolts are per ASME B18.2.6. In addition, the bolts material is Grade A325, Type 1 as defined in the ASTM F3125 specification.

5.2 Electric furnace and supporting frame

The furnace used in the experiments consisted of two semi-cylindrical electric ceramic heaters with vestibules on top and bottom, 2,700 W, 240 V, 304.8 mm (12”) in height, 406.4 mm (16”) outer diameter and 304.8 mm (12”) inner diameter as shown in [Figure 3\(a\)](#). Two ceramic end caps were used to close the top and bottom vestibules and form a closed chamber while allowing for wires and the vertical steel bars to pass through. [Figure 3\(b\)](#) shows the electric furnace setting on an adjustable steel frame that allows for positioning the furnace at a suitable height while holding it firmly in place.

The temperature inside the furnace was measured by two thermocouples inserted through the top cap. A computerized controller unit received the temperature readings and adjusted the temperature inside the furnace in accordance with a predetermined heating regime.

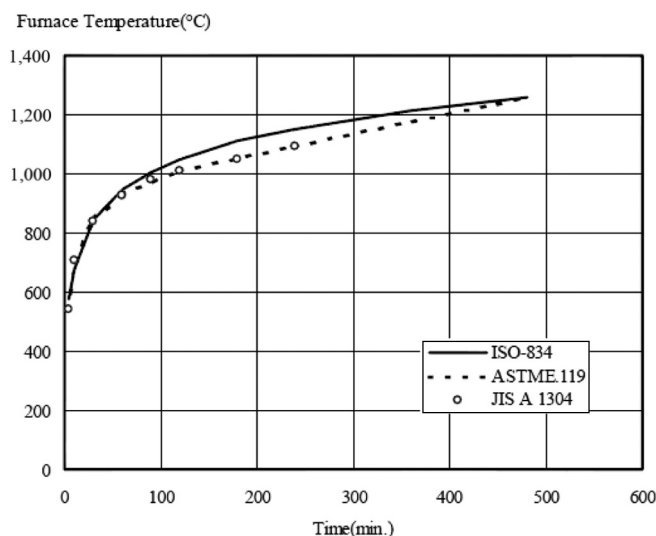


Figure 1.
Standard fire curves
(courtesy Al-Jabri
K.S.)

5.3 Testing procedure

Strain gage installation: The bolt shank was cleaned, abraded and neutralized before fitting a strain gage to it using a capacitive spot welder.

Bolt pretensioning: The tested specimen was assembled using a torque wrench to tighten the bolt between the top and bottom hollow structural sections, whereas the spacer piece provided enough room for the placement of the strain gage. The top and bottom steel bars were loosely attached to the tested specimen and the grips of the testing machine.

Load application: After closing the furnace and securing it inside the steel frame, a linear variable differential transformer (LVDT) was attached to the system to measure the vertical displacements. Afterwards, a tension load was applied to the vertical bars and increased at ambient temperature until reaching the desired load. This load was then maintained at a constant level to start the next step. Figure 4 shows the test setup just before heat application.

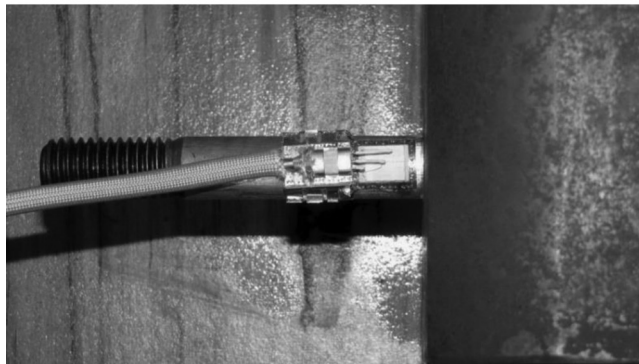
Heat application: A nonlinear temperature profile was adopted for all experiments. All the experiments were conducted using a transient-state method, which means that the tension load was maintained at a constant level during the experiment while the temperature was increased until failure.

The bottom of the inside chamber of the furnace was lined with a thick layer of ceramic fiber to ensure that no heat escaped from the bottom end-cap and to cushion the impact of the falling parts after the specimen has failed. Outside the furnace, on the top end cap, a similar layer of ceramic fiber is also used to prevent hot fumes coming out of the furnace from melting the electrical wiring attached to and coming out of the furnace. All other parts that were in danger of exposure to high temperatures were also protected with a layer of ceramic fiber.

A list of all performed experiments is shown in Table 1, the first four test were used to calibrate the equipment and choose an appropriate bolt size and tension load. The last three, which were identical, are the ones presented here and used for FE verification.



(a)



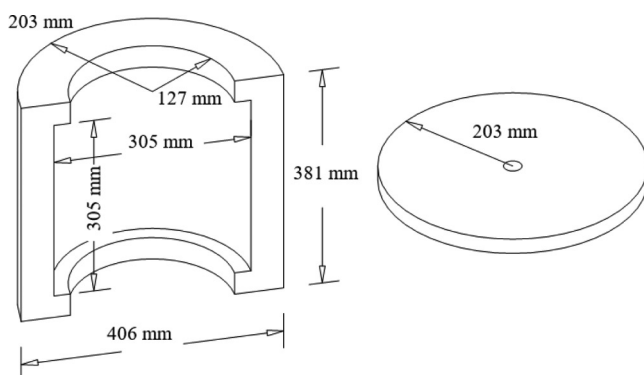
(b)

Figure 2.
(a) Assembled specimen; (b) the tested bolt

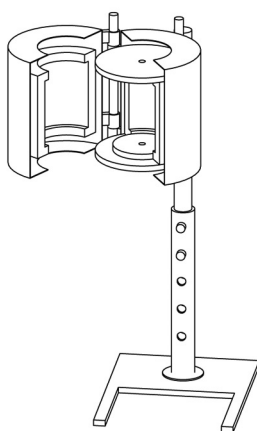
5.4 Data acquisition

A data acquisition unit was used to record the data generated from the tested specimen until its failure. This information was instrumental in verifying the finite element model. The data recorded included:

- *Temperature:* Two thermocouples (type K) were used to record the temperature of the steel specimen inside the furnace. The first thermocouple sent its data to the furnace controller unit, which was responsible for controlling the temperature inside the furnace. While the second thermocouple was attached to the main data acquisition unit. Both thermocouples were placed in direct contact with the top surface of the specimen.
- *Load:* The applied tension load was recorded through the load cell readings of the tensile testing machine (Tinius Olsen).



(a)



(b)

Figure 3.
(a) Electric furnace components; (b) an illustration of the furnace and its frame

- *Strain:* A strain gage fitted to the shank of the tested bolt measured strains in the bolt.
- *Displacement:* To monitor the deformations in the tested specimen until failure, an LVDT module was used to measure the displacement of the tensile machine. As a result, measuring the elongation in the entire specimen.

Other measurements of the specimen dimensions before and after each test where also recorded.

6. Test results

6.1 General observations

The progress of each test was carefully monitored until the specimen has failed. All tested bolts failed under tension in the threaded section at the root of the nut, showing considerable deformations at high temperatures. Figure 5(a) shows a comparison between the tested bolt before and after conducting the experiments. Figure 5(b) shows the failure pattern witnessed by all the tested bolts. The failure plane always occurred in the threaded area just under the nut. On average, 12.7 mm ($\frac{1}{2}$ ")-diameter bolts have elongated an extra 10.16-12.7 mm (0.4-0.5 inches) in length.



Figure 4.
Test setup before
starting the
experiment

Table 1.
A list of the
experiments
performed

Test	Maximum applied load [N]	Failure temperature [°C]	Bolt Diameter [mm]
1	120,000	20	12.7
2	26,700	545	12.7
3	8,896	880	19.1
4	8,896	550	12.7
5	8,896	580	12.7
6	8,896	600	12.7
7	8,896	610	12.7

For most of the conducted experiments, other than high-temperature oxidation in non-coated parts, shown in [Figure 6](#), the remaining parts of the tested specimen (steel sections, bars and nut) did not experience any discernable damage.

6.2 Specimen response

Before testing under high temperatures, bolts were tested in room temperature to verify material properties. [Figure 7](#) shows the stress–strain relationship for an A325 bolt.

The detailed response for a group of tests consisting of three experiments conducted under identical conditions is shown in [Figure 8](#) and [Figure 9](#). These experiments tested bolts 12.7 mm (½”) in diameter under a constant tension loading of about 8,896.44 N (2000-lb).

[Figure 8\(a\)](#) shows the tension load being increased for the first phase of the test and then it will remain constant during the heating phase. The transient-state test started after



(a)



(b)

Figure 5.
(a) Bolt comparison;
(b) failure surface

maintaining that constant load. [Figure 8\(b\)](#) shows a steady increase in displacement during the tension-loading phase, a more pronounced increase in displacement in a somewhat linear fashion up to 500°C (932°F), then a rapid deformation until failure. The temperature-displacement relationship shown in this figure defines the behavior of the tested bolts under high temperatures. This relationship can be used to verify a computational model as described in the following sections.

The cutoff point (or the end-of-test point) for each experiment has been chosen at the location where the tension load had its first sudden drop-off. The end-of-test point was also confirmed by measuring the dimensions of each specimen components before and after the test.

The results of the FEA were correlated to the results shown in [Figure 8\(b\)](#). The effects of time were neglected in the FE model although an investigation of the creep effects during fire may provide better insight into the failure mechanism.

7. Creep effects and more experiments

Due to the limitations and nature of the heater elements used during the experiments, a standard fire curve, such as that shown in [Figure 1](#), could not be achieved. [Figure 10](#) shows a comparison between a standard fire temperatures and the actual temperature regime followed during the experiments.

A standard fire reaches a temperature of 600°C in around 6 min, whereas it took the specimens about 40 min to reach the same temperature. This prolonged exposure to high temperatures introduces creep deformations to the experimental results because steel



Figure 6.
Rusted parts after the
end of the test

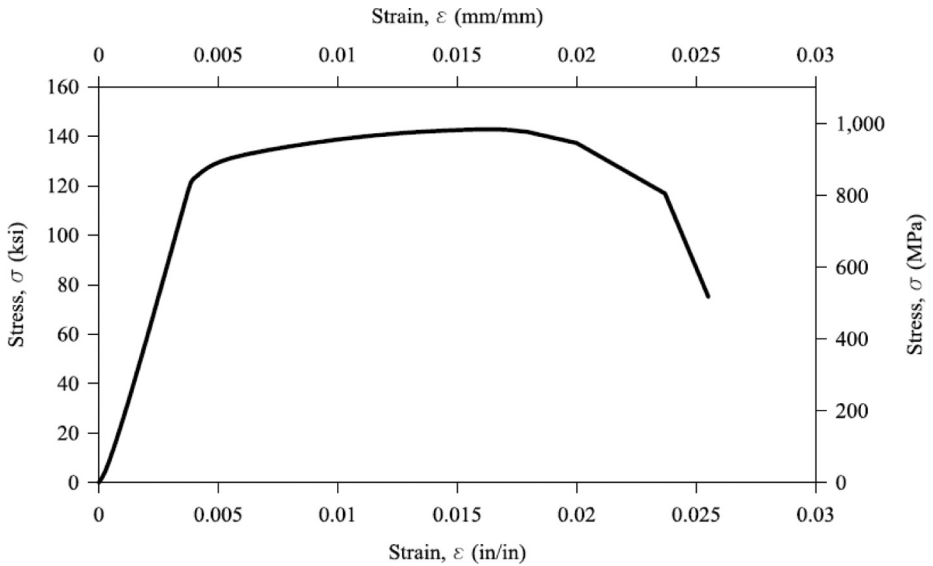


Figure 7.
Stress-strain curve of
ASTM A325 bolt
tested under ambient
temperatures

generally starts to exhibit significant creep behavior at temperatures close to one-third of its melting point, which is around 1,400°C (2,552°F). Additional research was conducted at the University of Wisconsin-Milwaukee by [Matar et al. \(2014\)](#) to investigate the effects of creep on similar experiments. As a result, four creep models were developed based on experimental data; three of those models predicted creep strain at constant temperatures of 450°C (842°F), 500°C (932°F) and 550°C (1,022°F). The fourth model, a general model, predicted the creep strain at any temperature within the range of 450°C (842°F) to 550°C (1,022°F) through data interpolation. Creep data are also being incorporated into the finite element model to refine the results at high temperatures.

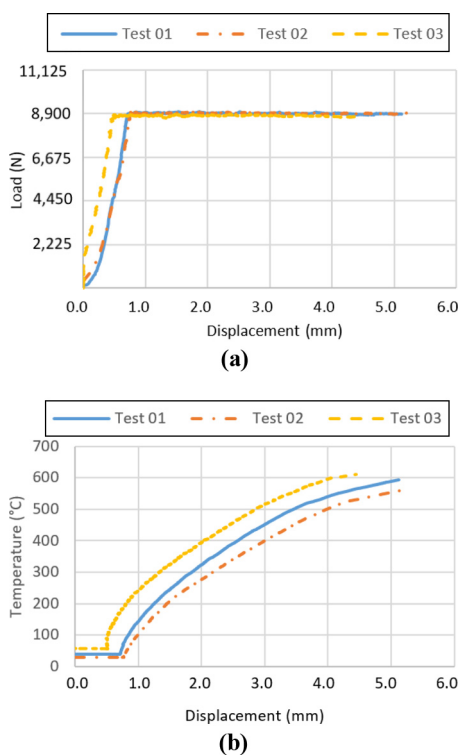


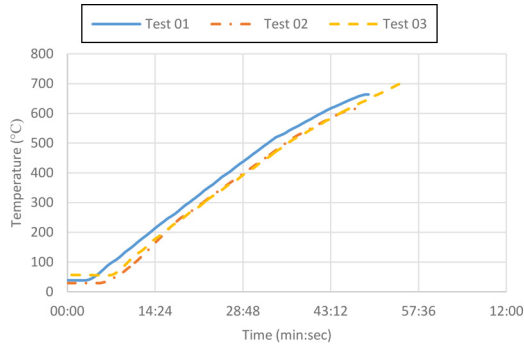
Figure 8.
(a) Load vs displacement; (b) temperature vs displacement

8. Finite element analysis

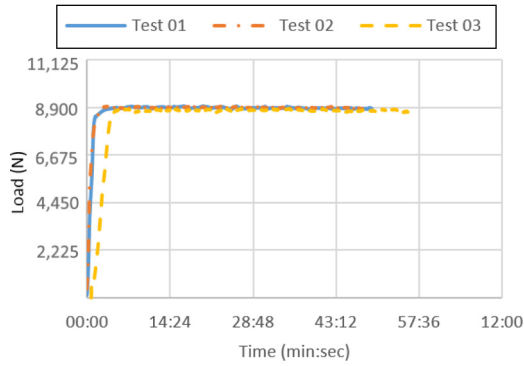
8.1 Model

Using the FEA software ANSYS v14.0, a detailed 3D model was generated of the tested assembly as shown in [Figure 11](#). The finite element model geometry is made to be parametric, so that future research is facilitated for any type of bolts and for different sizes. The parametric design is also useful for performing necessary sensitivity analyses. The general analysis process involved:

- creating the 3D model geometry;
- defining material properties of each element; sensitivity analysis is done to choose various material property values;
- identifying contact regions between various elements and setting up their properties;
- generating a suitable mesh of elements that represents the model with the least number of elements possible without compromising the accuracy of the analysis results;
- applying the test loads on the model and running the analysis; and
- reviewing the results and correcting problematic spots.



(a)



(b)

Figure 9.
(a) Temperature vs time; (b) load vs time

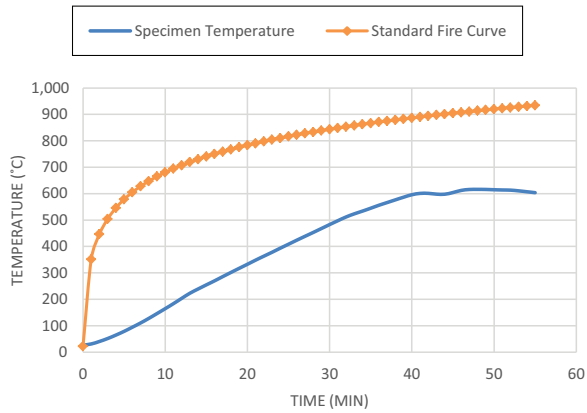


Figure 10.
Comparison between a standard fire and the temperature of the furnace

8.2 Results

The results of the finite element model were in close agreement with the experimental data especially up to a temperature of 500°C (932°F) as shown in Figure 12. After that, it displayed some signs of increased stiffness; this is because the FE model has no residual internal stresses, does not reflect impurities in the used materials, assumes continuous connectivity between components and assumes ideal geometric and boundary conditions.

Figure 13 illustrates the relationship and separation between the nut and bolt threads. This relationship was hard to monitor during the experimental tests; however, FE analysis offers an invaluable opportunity to inspect such critical places with ease. At higher temperatures, creep in the experiments can be present, whereas the FE model did not account for creep.

At ambient temperatures, it has been estimated that bolt failures are more likely to occur at three different locations; 15 per cent under the head, 20 per cent at the end of the thread and 65 per cent in the threads at the nut face. In all these places, the main culprit in causing failure is stress concentrations due to sudden geometric changes. Similar tendencies were noted as well under elevated temperatures.

9. Conclusions

The results from the experimental work show that the tested bolts are likely to collapse after the temperature has reach 600°C-700°C (1,112°F-1,292°F), and, below 600°C, the bolts will

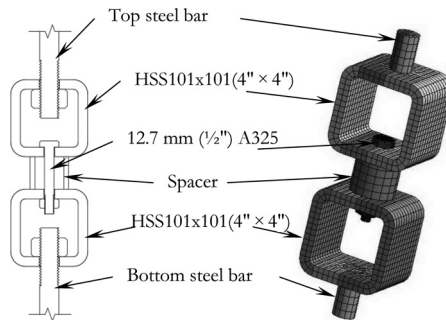


Figure 11.
3D finite element
model

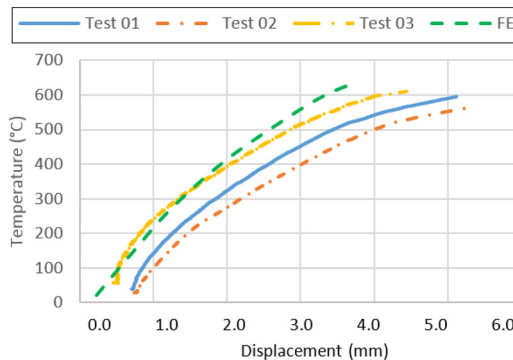
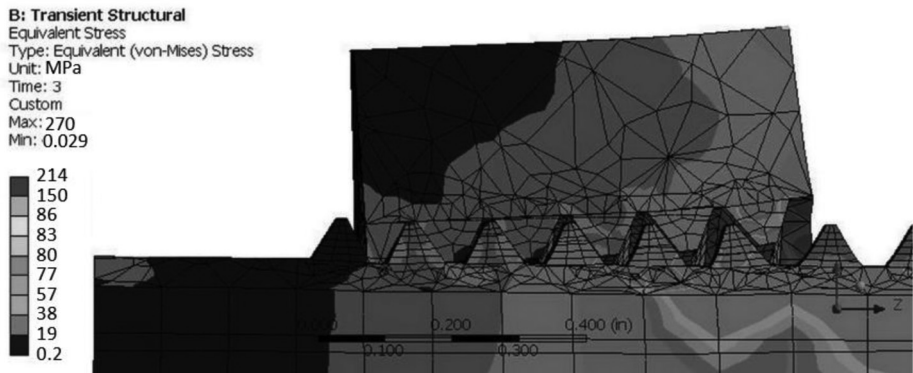


Figure 12.
FE response vs
experimental data

Figure 13.
Deformations near
the bolt threads



deform quite visibly. However, this result is dependent upon the bolt diameter and the applied load (which is about 10 per cent of the tensile strength). In a future investigation, the researchers will attempt to quantify the relationship between the bolt diameter, temperature and the applied tension load.

In an effort to simulate fire conditions, all experiments were conducted in a relatively short period of time. In situations where bolts are subjected to extended high levels of heat exposure, more research is required to know the exact effects of that prolonged heat exposure. The strain gage results were not meaningful at high temperatures (over 200°C). However, the results from the gage were useful in verifying pretensioning loads.

Further experiments are being conducted to address some of the limitations of the results obtained. Like the potential effects of creep and the inclusion of more bolt types and sizes (only A325 12.7 mm ($\frac{1}{2}$ ") and 19 mm ($\frac{3}{4}$ ") diameter bolts were tested.) Accounting to variations in the applied stress, bolt area, bolt length and exposure time will lead to the development of non-dimensional curves that can be used by practicing engineers in daily design procedures.

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