Al-Rafidain Journal of Engineering Sciences

Journal homepage https://rjes.iq/index.php/rjes

ISSN 3005-3153 (Online)

Post Fire Performance Of Thin-Walled Carbon Steel Single Shear Bolted Connections

Rahma Ghassan[1], Sarah Yahya[1], Hosam Ahmed[1]

[1] Department of Civil Engineering AL-Farabi University College, Baghdad, Iraq

ARTICLE INFO

Article history:

Received 29 October 2025
Revised 5 November 2025
Accepted 3 December 2025
Available online 4 December 2025

Keywords:

Carbon steel
Bolt connection
Net section fracture
Curling displacement
Post fire behavior

ABSTRACT

Evaluation of a steel building after a fire is very important for the determination of the reuse of post-fired steel components. This research is aimed at studying the post-fire behavior of single-shear bolted connections. It examines the influence of some of the key parameters, including end distance, edge distance, and spacing between bolts, on the behavior of the connection after exposure to fire. The specimens were heated to 1000 °C and cooled by water. After heating and cooling of the specimens, some physical changes were noted; the first was the deformation (curvature), and its amount was greater as the surface area of the specimen increased. In addition, a decrease in the thickness of the specimens was recorded. The reduction in the thickness of the specimens was about 18%, which must be taken into consideration in the redesign of the steel structure after it has been exposed to fire. The majority of the specimens failed by net tensile fracture. Some of the specimens with relatively large end distance showed curling displacement before failure. Only one specimen failed by end-distance fracture without curling displacement.

1. Introduction

Modern building construction requires a large number of pipes and conduits, including occupational safety pipes for firefighting. These pipes in concrete buildings pass through holes in structural elements that lead to decreased stiffness in construction members. Conversely, the passage of the service pipe network has no effect on the steel design of the building (Ali, & Said, 2022) [1]. Due to its benefits in load-bearing capacity, strength-to-weight ratio, seismic performance, and energy efficiency, steel structures have been widely used in both residential and commercial buildings, including skyscrapers, long-span bridges, and airport terminals. However, catastrophic events like earthquakes, floods, explosions, and fire can occur over the lifespan of structures, causing structural failure, financial damage, and occasionally even casualties. (Shi, et al., 2022; Piroglu, et al., 2017) [2,3]. Connections are a significant part of steel construction because they have a direct influence on the failure resistance and structural integrity of steel buildings (Akagwu, et al., 2020) [4]. During a fire, a steel structural parts may be subjected to high temperatures. After a fire, steel buildings need to have their structural safety verified. Understanding carbon steel's post-heating behavior is necessary for this evaluation (Sulayman, & Mahmood, 2021) [5]. Fire situations reduce the strength of the steel structure and can cause collapse, resulting in losses, hence the impacts of fire must be considered when planning construction. Given that joints influence the performance of steel structures, research on the performance of steel beams should be enhanced by examining the

Corresponding author E-mail address: rahmaghassan996@gmail.com

https://doi.org/10.61268/wxyge435

post-fire bolted connection performance (Gunadi, et al. 2020) [6]. The structural behaviour of cold-formed steel members has been investigated extensively, including beams and columns (Laim, et al., 2013; Wang & Young 2014) [7,8], (Young & Rasmussen 1998; Young & Hancock 2003) [9,10]. beam-columns (Torabian, et al., 2015; Torabian, et al., 2016) [11,12] and built-up sections (Fratamico, et al., 2018; Cai & Young 2020) [13,14] increasingly used in low-rise buildings, multi-story structures, and long-span structures due to their strength-to-weight ratios and ability to fabricate complex shapes (Huynh, et al., 2020; Truong & Pham 2021) [15,16]. The curling (out of plane displacement) was shown to control the strength of thin bolted connections between (Pham, et al., 2023) [17]. Because of the serious consequences that a fire can cause, there has been an increase in research on building fire safety in recent decades (Chen et al., 2006; Fratamico et al., 2018). [18, 13], (Tao et al., 2013; Wang & Young, 2016) [19, 20]. The material itself, the highest temperature attained during the fire, the amount of time spent soaking at a high temperature, and the cooling technique all affect how fire affects the mechanical qualities of steel elements (Molkens et al., 2021) [21].

A finite element analysis for lean duplex stainless steel single-shear four-bolted connections with a nominal plate thickness of 3.0 mm was conducted by (Kim, et al., in 2020) [22], curling was found to reduce ultimate strength by as much as 29%. Strengths were compared with output of some analytical models from earlier studies and design specifications. A modified equation has been proposed that takes into account both the actual fracture mode at the ultimate state and the impact of curling on strength, in the same year (Mahmood, et al.,2020) [23], investigated the effect of the end distance on the behavior of carbon steel bolt connections by a finite element analysis, and it was found that the connection strength clearly improved as the end distance increased. As a result, it was suggested to keep the maximum end distance to 50 mm.

In 2022 Sulayman & Mahmood [24], performed an experimental study for thirty-four bolted connection specimens and thirty-four coupons. They were heated to 400 °C and 700 °C for (30, 60, 90, 120) minutes and then cooled either by air or water. The results of the study showed that high temperature exposure to steel caused some physical changes, primarily a reduction in thickness. The yield stress and elastic modulus were most affected by the heating temperature and duration. The cooling technique has the least effect. The failure mechanisms of the coupons and the bolted connections were unaffected by the heating temperature or cooling method. The coupons failed as a result of a typical tensile fracture, and the bolted connections failed in block shear with curling. The post-fire mechanical parameters can be used to predict the connection's post-fire strength with accuracy. To keep the structure's components strong, it is advised to put out the fire with water. (Molkens et al., 2021) [21] discovered that because of the size of the surrounding components, the temperature of connections during a fire is frequently lower than that of the surrounding members. Additionally, any damaged bolts can be readily replaced after the fire, reducing the negative economic impact of the fire. Recent testing on a variety of carbon steel bolts (M6 to M24, grades 8.8 and 10.9) produced similar results. It was shown that heating the materials to 500 oC had no effect on their mechanical properties. Instead, significant changes in the properties were seen at higher temperatures.

The purpose of this study is to comprehend how thin-walled carbon steel bolted connections behave after a fire. The impact of bolt spacing, end distance, and edge distance on the overall behavior of the connection exposed to fire was examined experimentally in order to accomplish this goal.

2. Experimental Work

Nine carbon steel specimens of 4mm thickness connected via four M14 bolts and variable end distance (a), edge distance (b) and spacing between bolts (g&p) (Fig. 1) were heated, cooled and tested. Specimens were prepared with the required dimensions and bolt holes then placed in the furnace for heating to 1000 ̊ C for 120 min. Then, specimens were immersed in water for cooling purposes. A thick pulling plate with dimensions of 185×300×16 mm was used for pulling the specimens during the test. The specimens were connected to a thick pulling plate (185×300×16 mm) by four M14 bolts. Two strain gages were used (first one fixed next to the bolt along the end distance and the other one to the side of the bolt) (Fig. 3). Linear Variable Differential Transformer (LVDT) were used to record the curling displacement. After the test the values of (load, strain, vertical and horizontal displacements) were recorded and the type of failure of specimens were also identified. The parameters limits are shown in Table (1) and Fig. 4. The limitation (minimum and maximum limits) of this study were compared with those limitations for both AISC Specifications and Eurocode of bolted connections as presented in Table (2).

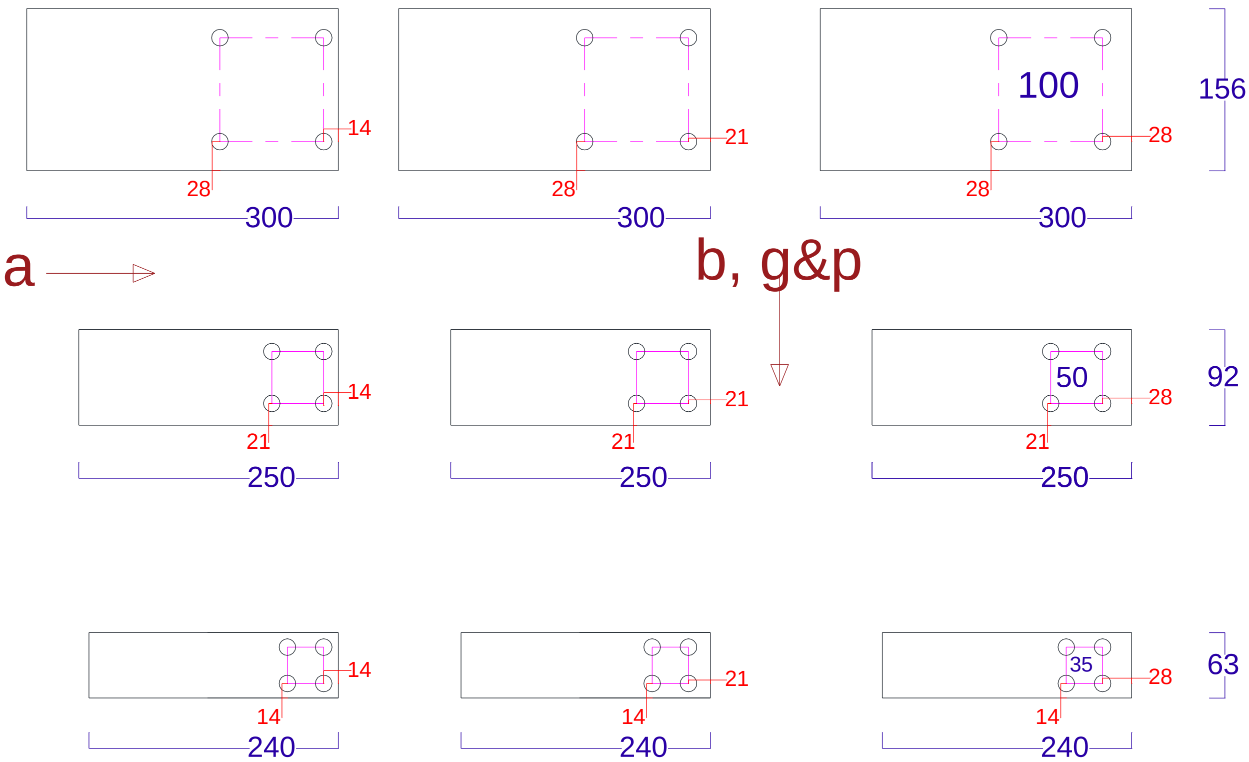

Figure 1. Specimens' details (all dimensions in mm)

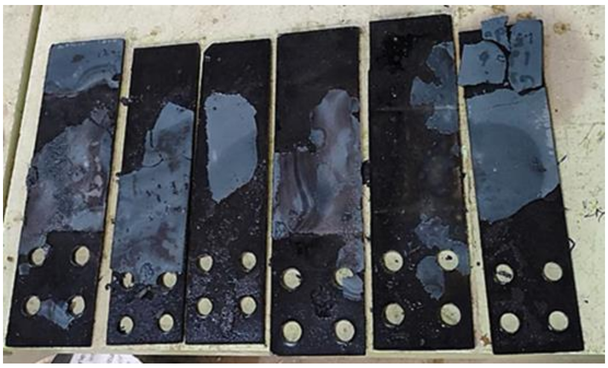

Figure 2. Specimens after heating and cooling

Figure 3. Location of strain gage on specimen

Table 1: Parameters limits

a , b	g , p
1 × d bolt	2.5 × d bolt
1.5 × d bolt	3.5 × d bolt
2 × d bolt	25 × t

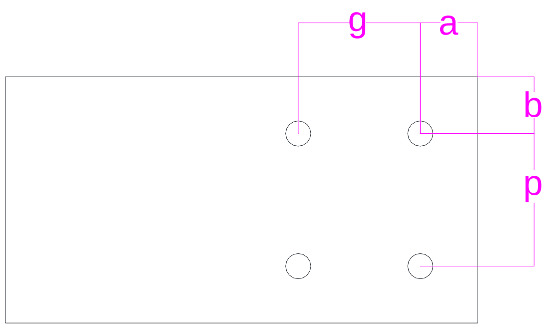

Figure 4. Specimen parameters

Table 2: Max. and min. (a, b, g & p) of this study compared with AISC manuel and Eurocode

	End distance (a)		Edge distance (b)		Spacing of bolts (g&p)	
	Min.	Max.	Min.	Max.	Min.	Max.
This Study	14 mm	28 mm	14 mm	28 mm	35 mm	100 mm
AISC	(1.25db) 17.5 mm	(12t) 48mm	(1.25db) 17.5 mm	(12t) 48 mm	(3db) 42 mm	(24t) 96 mm
Eurocode	(1.2db) 16.8 mm	(4t+40) 56 mm	(1.2db) 16.8 mm	(4t+40) 56 mm	(2.2db) 30.8 mm (2.4db) 33.6 mm	(14t) 56 mm

3. Result and Discussion

It was found that peeling surface layers of all specimens after heating and cooling can be considered as 18% decreasing in thickness of the specimens and this must be taken into consideration in the redesign of steel structure after it has been exposed to fire (Fig. 5). The type of failure for eight specimens was net section fracture failure, some of them shows curling displacement. While the ninth specimen was failed by end distance fracture failure and without curling displacement. This difference of failure types happens due to the difference of the specimens' dimensions and parameters like end, edge distances and bolt spacing. Accordingly, the failure tracks the shortest path. So, when the specimen has smaller width, it takes the net section as a failure path and failed with net section fracture. When the specimen became wider, the failure tracks the shortest path to achieve the specimen failure, which was end distance fracture that happened with the specimen of b=14mm, p&g=100 mm.

Figure 5. Peeling surface layers and deformation (bending) of large specimen

Table 3: Results of specimens (4 mm-1000 °C - cooled in water)

Specimens	Yielding Load Py (kN)	Ultimate Load Pu (kN)	Max. Curling displacement (mm)	Curling Load (kN)	Ductility $(\frac{\text{Long. disp. at Pu}}{\text{Long. disp. at Py}})$
b14 a14 g&p35	62	75.089	0	-------	1.95
b14 a21 g&p35	67	77.378	0	-------	1.76
b14 a28 g&p35	61	90.2	0	-------	2.23
b21 a14 g&p50	92	155.956	0	-------	1.76
b21 a21 g&p50	162	181.148	0.979	76.199	1.64
b21 a28 g&p50	130	166.303	0.861	24.118	2.08
b28 a14 g&p100	221	250.184	0	-------	2.65
b28 a21 g&p100	255	309.567	4.293	40.153	3.29
b28 a28 g&p100	248	270.6	6.392	72.005	1.98

In Table (3) the results of the tested specimens are presented and it shows that the strength decreases when curling displacement appears with the increasing of end distance, and it was found that the curling displacement showed reduction as the entire dimensions of specimen decreased.

Figure 6. Specimens with (b=14 mm, g&p=35 mm)

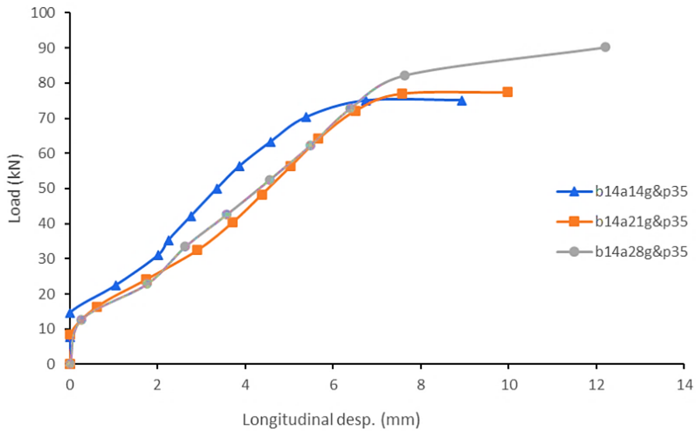

Figure 7. Load VS longitudinal displacement

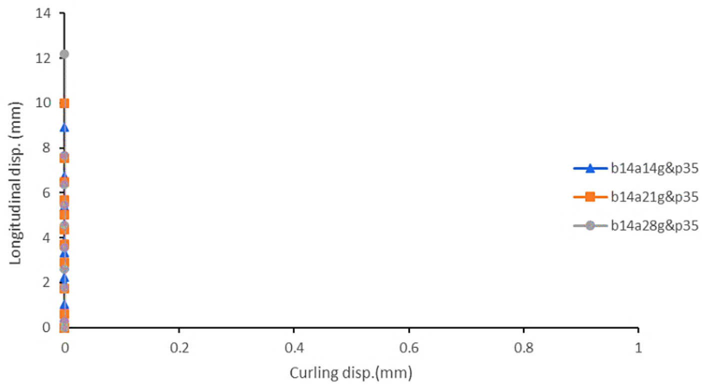

Figure 8. Longitudinal displacement VS curling displacement

The specimens with edge distance 14 mm and bolt spacing 35 mm, (b14a14g&p35, b14a21g&p35, b14a28g&p35) failed by net section fracture (Fig. 6). These specimens showed increasing of the ultimate load when their end distances increase, they show enhancement in ductility when the end distance was increased (Fig. 7). Also, they had no curling displacements only longitudinal displacements. This is likely due to the small dimensions of the specimens, which means a faster failure path for net tensile fracture to occur. (Fig. 8).

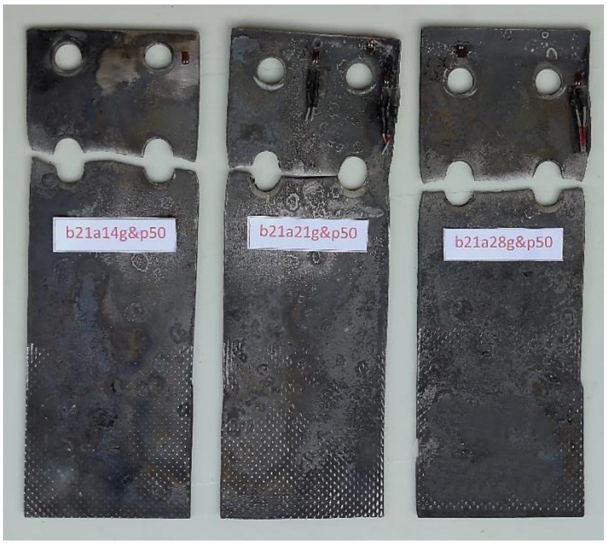

Figure 9. Specimens with (b=21 mm, g&p=50 mm)

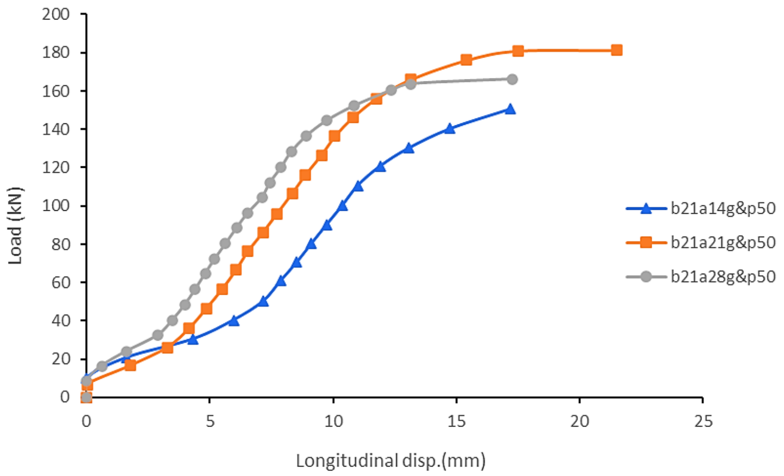

Figure 10. Load VS longitudinal displacement

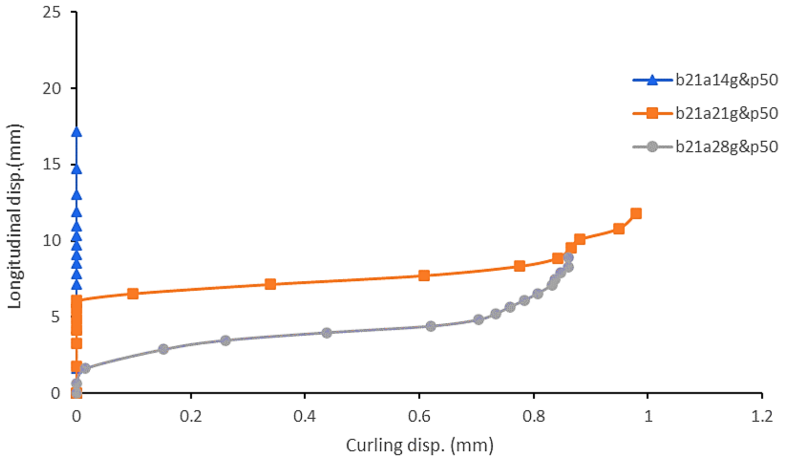

Figure 11. Longitudinal displacement VS curling displacement

Specimens of edge distance 21 mm and bolt spacing 50, (b21a14g&p50, b21a21g&p50, b21a28g&p50) the type of failure was also net section fracture failure (Fig. 19). The ultimate load was higher in the specimen that had the end distance 21mm (b21a21g&p50) but its ductility was the lowest (Fig. 10). The curling displacement accrued in two specimens which have the higher end distances. For these specimens (b=21, g&p50 mm) the path of net section fracture became a little longer resulting from the wider specimen dimensions so curling displacement started to appear slightly (Fig. 11).

Figure 12. Specimens with (b=28mm, g&p=100mm)

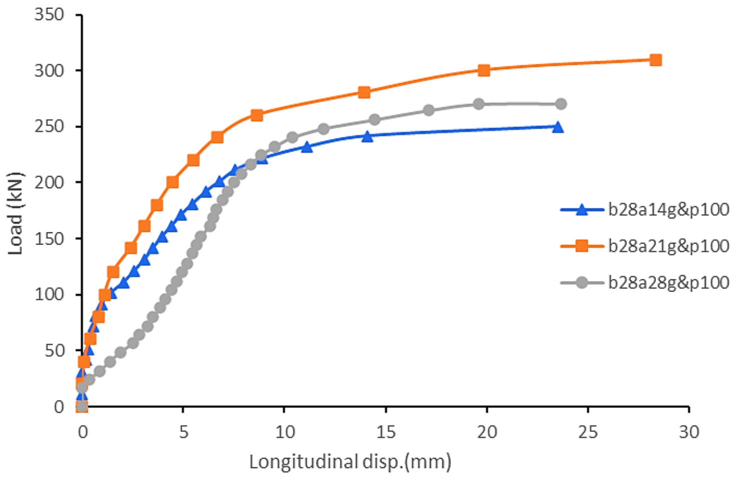

Fig. 13 Load VS longitudinal displacement

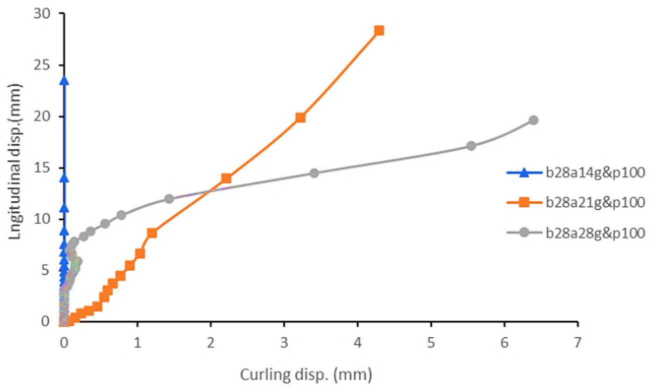

Figure 14. Longitudinal displacement VS curling displacement

For the specimens with edge distance 28 mm and bolt spacing 100 mm, (b28a14g&p100, b28a21g&p100, b28a28g&p100) the type of failure was net section fracture for specimens (b28a21g&p100, b28a28g&p100), while the specimen with end distance 14mm (b28a14g&p100) was failed by bending fracture along the end distance and without curling displacement (Fig.12). It is possible that this type of failure occurred due to the small end distance compared to edge distance and the spacing between bolts. The higher value of ultimate load was with the specimen (b28a21g&p100), and it has the highest ductility (Fig.13). However curling displacement appeared in the specimens with the highest end distance (21,28 mm) (Fig.14). Also, with these specimens and as a result of the long net tensile fractur failure path, if compared with the rest of the specimens, it was a reason for the appearance of curling displacement. As for the specimen, which had a very small end distance (14mm), it provided a very fast failure path due to this small distance, so it failed bending fracture along the end distance.

4. Conclusion

In this paper parametric study on single-shear carbon steel connection was performed. Nine specimens with different dimensions (end distance, edge distance and spacing between bolts) the study was conducted to understand the behaviour of single-shear bolted connection of carbon steel after exposure to fire, and specifically to understand the effect of the end and edge distance on the general behaviour of post fired connection. Several conclusions were reached through this research, including:

- Physical changes can occur after exposing to high temperatures (1000˚C) and cooling with water:
  - The curvature of specimens because of the high and fast cooling and the curvature amount was noted to be higher as the specimen surface area was larger.
  - All specimens showed reduction of thickness by about (18%), and the other dimensions did not seem to be greatly affected. The cross-sectional area of the steel decreases as a result of this change in thickness, which also reduces the load-carrying capacity. And this point needs to be considered when redesign the post fire steel structures.

- After specimens' tests two types of failure modes were recorded of the specimens in this study,
  - Net section fracture failure, which occurred for most of the specimens and some of these specimens was accompanied by a curling displacement, while curling displacement in the others were not recorded.
  - Bending fracture failure along the end distance, which occurred only in one specimen, and it was not accompanied by curling displacement.
- The curling displacement appears when the specimen has relatively large dimensions and the end distance is twice the diameter of the bolt or more.
- Through the specimens which had a curling displacement, it was noted that the curling displacement limit the strength improvement of the specimens.
- The type of failure affected by the specimen dimensions by controlling the path of rapture through which specimens fail, as they increase, the distance between the bolts increases, thus providing a relatively long path for the net tension fracture, thus, the curling displacement begins to appear.

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