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Behavior of Steel Beams Subjected to Bending and Shear Loading Under Localized Fire Conditions

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A B S T R A C T

Civil structures were designed to carry a variety of loading during their service life, including fire hazards. As a result, providing fire safety to structural members is one of the most important tasks in civil infrastructure design. Steel structural members are subject to fire-induced damage or collapse due to their high heat conductivity and quick loss of strength and stiffness qualities. Furthermore, the failure in steel beams under the combined effects of bending, shear, and fire loading is poorly understood in the literature. A present study consists of experimental investigations on the fire response of steel beams under bending and shear dominant loading. The specimens have a constant length of 1250 mm. The total depth of the specimens was changed according to the section chosen: 4 in, 6 in, and 8 in (10 cm, 15 cm, and 20 cm). The results of tests show that beams can fail suddenly due to a high drop in yield and ultimate strength of the steel beam. the increase in temperature degree reduced greatly the yield and ultimate flexural strength of the steel beams with different sizes (for all groups). This reduction reached at some times to 50% for the ultimate strength capacity of the specimen. Shear strength is also affected greatly by fire exposure and the reduction reached to about 38%. Furthermore, the design strength capacity can only tolerate loads at low temperatures. This reduction in strength was noted under flexural and shear dominant loading. Moreover, the design strength capacity can withstand against loading at low-temperature degrees only.

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تصرف العتبات الفولاذية المتعرضة الى احمال انثناء وقص تحت ظروف الحريق

عمر فاروق ابراهيم قسم الهندسة المدنية / كلية الهندسة / جامعة تكريت / تكريت - العراق.
حفصة علي عبدالله قسم الهندسة المدنية / كلية الهندسة / جامعة تكريت / تكريت - العراق.

الخلاصة

تم تصميم الهياكل المدنية لتحمل مجموعة متنوعة من الأحمال خلال فترة خدمتها، بما في ذلك مخاطر الحريق. نتيجة لذلك، يعد توفير السلامة من الحرائق لأجزاء الهيكل أحد أهم المهام في تصميم البنية التحتية المدنية. تتعرض العناصر الهيكلية الفولاذية للتلف أو الانهيار الناجم عن الحريق بسبب التوصيل الحراري العالي والفقدان السريع لخواصها من حيث القوة والصلابة. علاوة على ذلك، فإن الفشل في العوارض الفولاذية تحت التأثيرات المشتركة للانحناء والقص وتحميل النار غير مدروس جيدًا في البحوث العلمية. تتكون الدراسة الحالية من تحقيقات تجريبية حول استجابة العوارض الفولاذية للحريق تحت التحميل السائد للقص والانحناء. العينات لها طول ثابت 1250 مم. تم تغيير العمق الكلي للعينات وفقًا للقسم المختار: 4 بوصات و6 بوصات و8 بوصات (10 سم و15 سم و20 سم). تظهر نتائج الاختبارات أن الحزم يمكن أن تفشل فجأة بسبب الانخفاض الكبير في نقطة الخضوع والقوة النهائية للعارضة الفولاذية. أدت الزيادة في درجة الحرارة إلى انخفاض كبير في المحصول وقوة الانحناء القصوى للعوارض الفولاذية ذات الأحجام المختلفة (لجميع المجموعات). وصل هذا التخفيض في بعض الأحيان إلى 50٪ من أجل قدرة القوة القصوى للعينة. تتأثر مقاومة القص أيضًا بشكل كبير بالتعرض للحريق ووصل الانخفاض إلى حوالي 38٪. علاوة على ذلك، فإن قدرة قوة التصميم لا يمكنها تحمل الأحمال إلا في درجات حرارة منخفضة. لوحظ هذا الانخفاض في القوة تحت التحميل السائد للثني والقص. علاوة على ذلك، فإن قدرة قوة التصميم يمكن أن تصمد أمام التحميل عند درجات الحرارة المنخفضة فقط.

الكلمات الدالة: العتبات الفولاذية، حريق، الانبعاج الموضعي، سيطرة القص.

1. INTRODUCTION

Civil structures, such as buildings and bridges, is designed to serve occupants and users for many decades with safe behavior against structural stress and risks, such as fire, over their lives. and other accidental damages over their lives. Due to modern lifestyle rapid urbanization and increased use of combustible materials in buildings and other occupancies, causing fire accidents in these structures, the number of fires in high-rise buildings and civil structures has increased [1, 2]. Fire is a significant design parameter due to its destructive nature that can cause structural systems, as well as property to serious damage due to quick rises in steel temperatures (due to high thermal conductivity and low specific heat). As a result, structural steel elements can quickly lose substantially their load-bearing capacity in a fire [3, 4]. The controlling loading on beams and girders in a normal building is the bending moment, hence bending is the character in the design of beams at a normal temperature [5, 6]. The design of beams against shear is considered a secondary requirement in the design of steel beams. However, limited studies have been done on steel beams under the effect of bending and shear stress under fire exposure. Vimonsatit et al. [7] evaluated a variety of isolated steel beams (UC 152×152×23 kg/m and UC 203×203×52 kg/m) with 1600 mm span length to assess shear effects on beams under fire activity. The hot-rolled beams had web slenderness of 26.3 and 25.6. Under steady-state temperature conditions of 400°C, 550°C, and 700°C, the tested specimens were primarily loaded in shear. The top and bottom flanges of these beams were stiffened to prevent failure in the bending mode. They stated that the shear limit state should be considered in analyzing the failure of steel beams under fire circumstances since the data showed that the shear capacity of steel beams reduced dramatically with increasing temperature. Kodur and Fike [8] performed a fire resistance test on a 4000 mm length W12×16 A992 steel beam that was exposed to ASTM E119 standard fire. The flange and web slenderness of the tested beam were 7.5 and 49, respectively. To obtain a 2-hour fire resistance rating, the beam was insulated with 50 mm thick spray-sprayed vermiculite-based fire insulation. Two-point loads were applied to the beam. Due to lower temperatures in the steel beam flange, the moment capacity in the beam remained intact for the first 75 minutes under fire conditions. Shear capacity began to deteriorate at 35 minutes due to a faster rise in web temperature. When the temperature in the steel section hits 350°C after 75 minutes, the moment and shear capacity degraded even more. The steel section's moment capacity continues to deteriorate until 130 minutes when the beam fails because the capacity at mid-span falls below the moment owing to applied loading. Shear capacity did not decrease below the shear force near the support section, however, due to the low applied shear force, there were no symptoms of web local buckling. Choe et al [9] tested simply supported W16×26 steel beams having a 6170 mm long. The effect of prescribed heat release and structural fire test was the main parameter evaluated in the study. The heating rate of the specimens was affected by the prescribed heat release. Combined flexural and lateral-torsional failure was noted in specimens tested under a structural fire test scenario. Naser [10] studied the response of steel and composite beams under the combined effect of shear and fire exposure loading. One full-scale W24×62 with a 4165 mm span was constructed and tested. The results were verified with the finite element method and the parametric study was adopted by the ANSYS program to investigate the behavior of specimens under the dominance of shear and fire exposure. It's concluded that there was a clear degradation in the shear strength of composite beams under thermal conditions and the local torsional buckling was controlled on the response of the specimen. Ramesh et al [11] tested two I-section steel beams under the effect of flexural and localized fire effects. The 6200 mm span specimen was loaded using a four-point flexural loading scheme. The mid-span of specimens was exposed directly to a natural gas fire flame. The heat exposure ranged from 200 to 600 C. the main parameter investigated was the end restraints. It's concluded that both specimens show similar failure modes regardless of their end restraints. The specimens failed under the combined effect of flexural and torsional buckling. A quick survey in the above literature shows that limited studies have investigated the experimental response of steel beams after being subjected to structural and fire loading. The main purpose of this study is to conduct through an experimental program, the behavior of steel beams subjected to bending and shear loading under different fire conditions. The parameters considered were specimen size, loading type, and temperature degree. In the following section, the experimental programs will be presented.

2.TEST SETUP

Twenty-Four hot-rolled steel beams are designed according to AISC specifications [12]. These beams are not provided with any fire protection and to investigate the steel beam bending and shear strength under the combination of thermal (fire) and structural loading. W- sections are chosen in the present study according to the AISC specifications. These sections are used commonly in the steel construction of single and multi-story buildings. W4×4, W6 ×11, and W8 ×16 cross-sections are adopted in the present study (i.e W10×6, W15×16 and W20×24 kg/m). The specimens have a constant length of 1250 mm designed as a simple support beam, are fully braced laterally, and have a compact cross-section [12]. The steel sections are fabricated using A36 steel i.e., have a yield strength of 36 ksi (250 Mpa), which is commonly used in typical civil engineering applications. The experimental program consists of investigating the behavior of twenty-four steel beams. The tested specimens are grouped into two main categories: bending and shear test. Under these main categories, there are three groups classified according to beam size tested under three temperature conditions. Table 1 summarizes the tested specimens in the present study under the dominant bending load.

Table 1. Specimens' details tested under bending control

	Beam Name	Total depth (cm)	Temperature (C)
	W10BN	10	Normal
	W10B200	10	200
G1	W10B400	10	400
	W10B600	10	600
	W15BN	15	Normal
	W15B200	15	200
G2	W15B400	15	400
	W15B600	15	600
	W20BN	20	Normal
	W20B200	20	200
G3	W20B400	20	400
	W20B600	20	600

The specimens subscripted as followed Wd-L-T, where W: w-section, d: specimen depth (10, 15, and 20 cm), L: loading type (B: bending, S: shear), T: applied temperature (ambient, 200, 400, 600 C). For example, W20B400 means the specimen of 20 cm depth tested under the effect of bending and 400C loading. Table 2 lists the tested specimens under the dominant shear load.

Table 2. Specimens details tested under shear control

	Beam Name	Total depth (cm)	Temperature (C)
	W10SN	10	Normal
	W10S200	10	200
G1	W10S400	10	400
	W10S600	10	600
	W15SN	15	Normal
	W15S200	15	200
G2	W15S400	15	400
	W15S600	15	600
	W20SN	20	Normal
	W20S200	20	200
G3	W20S400	20	400
	W20S600	20	600

The fire resistance tests on steel beams are carried out at the heavy structure laboratory of civil engineering at Tikrit University. This fire test has been designed to produce varying conditions of heating scenarios (temperature-time curves) by following the ASTM E-119 and structural loading, similar to that a steel beam might experience during an actual fire incident [13]. Fig.1 gives a comparison between the experimental and the ASTM E119 specification. It can be seen that there is a good agreement between the applied and ASTM standard temperatures up to the first 3.0 minutes (till 250˚C). Then, the applied temperatures tend to be lower than the standards. It can be also seen that both temperatures converged towards the later stages of fire exposure.

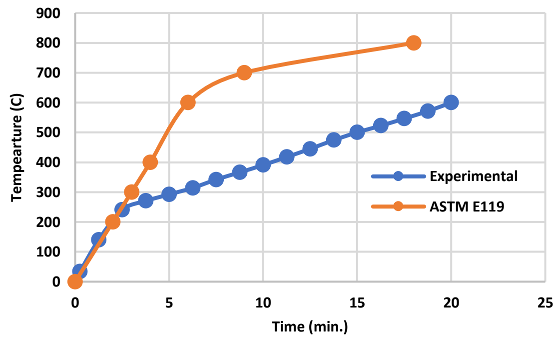

Fig. 1 Comparison of experimental and ASTM E119 temperature as a function of fire exposure time.

The fire test mechanism is comprised of a simply supported steel beam with fire sources applied at a specific location in the maximum bending moment and the maximum shear region as detailed in Fig.2 and Fig.3. The value of shear span "D" was considered to be equals to total beam depth. This fire source can produce a maximum heat energy of 2.5 MW using two gas burners located at the required region.

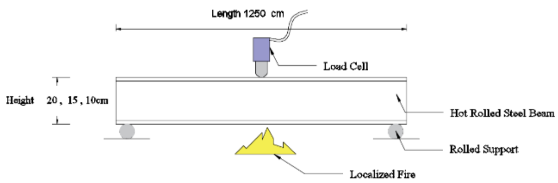

Fig. 2 Geometric configuration of tested beams under bending dominant.

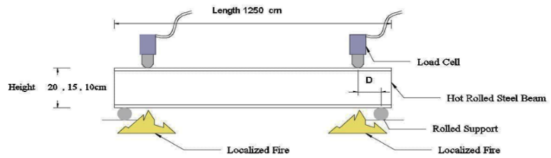

Fig. 3 Geometric configuration of tested beams under shear dominant.

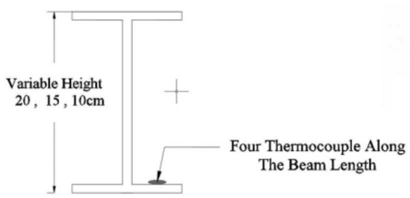

Fig. 4 Locations of thermocouples.

Four Types-K Chromel-alumni thermocouples are mounted along the beam section to monitor the actual progression of temperature. During the fire test, the gas supply is manually adjusted such that the temperatures follow a pre-determined fire curve (standard or design (realistic)), see Fig.4. A load cell was adopted to measure the actual applied load on the beam. Vertically oriented Linear Variable Displacement Transducers (LVDT) were attached to the beam mid-span to measure the vertical deflection. All data were measured by a data logger and saved by a computer program, so that, the values of P_y and P_u can be traced easily.

Fig.4 Specimen of Group 3 under bending and thermal loading.

3.EXPERIMENTAL RESULTS

3.1. Flexural response of tested beams

The most important characteristics of the flexural response of steel beams under three-point and thermal loading was listed in Table 3. The table reviews: the yielding load (P_y), ultimate load (P_u), and related mid-span deflection, Δ_y and Δ_u, respectively.

Table 3. The results summary of tested steel beams under bending control

	Temperature	P_y (kN)	Δ_y (mm)	P_u (kN)	Δ_u (mm)	Decrease in P_y (%)	Decrease in P_u (%)
Group 1	Normal	26.64	-5.4	29.16	-14.46	0	0
	200 C	23.9	-6.8	27.9	-20.0	10.3	4.32
	400 C	20.2	-7.2	21.87	-31.1	24.2	25.0
	600 C	12.8	-8.1	15.0	-50.0	51.9	48.6
Group 2	Normal	104.5	-3.2	120.0	-9.0	0	0
	200 C	90.2	-4.0	114.0	-14.0	13.7	5.0
	400 C	70.8	-5.1	86.4	-24.8	32.2	28
	600 C	51.0	-8.0	65.0	-38.0	60.4	45.8
Group 3	Normal	186.49	-4.6	223.16	-9.1	0	0
	200 C	178.2	-5.5	209.1	-10.1	4.4	6.3
	400 C	140.75	-7.75	170.0	-21.6	24.5	23.8
	600 C	129.6	-13.0	140.0	-30.0	30.5	37.2

It's clear from the listed results in Table 3 that the increase in temperature degree reduced greatly the yield and ultimate flexural strength of the steel beams for all sizes (for all groups). This reduction reached at some times to 50% for the ultimate strength of the specimen. Fig. 5 explains clearly the drop in ultimate flexural strength capacity of the Group 1 steel beams after expositing to high levels of temperatures.

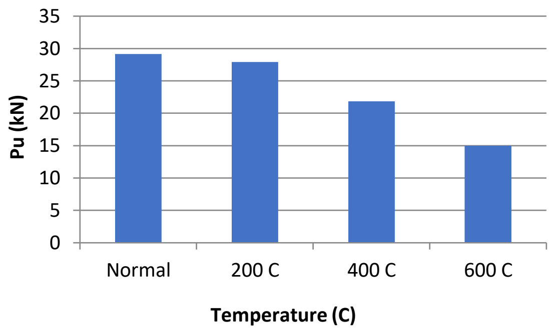

Fig. 5 Degradation of flexural capacity with temperature for Group 1 beams.

Fig. 6 explains also the ultimate strength capacity of specimens classified under Group 3. The effect of temperatures appeared clearly at values ≥ 400 C regardless of the size of a steel beam.

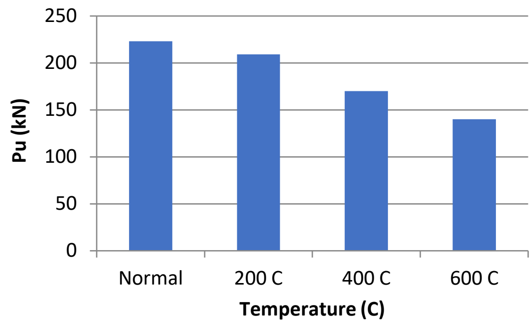

Fig. 6 Degradation of flexural capacity with temperature for Group 3 beams.

3.2. Shear response of tested beams

The characteristics of the shear response of steel beams under four-point and thermal loading was listed in Table 4. The table reviews: yielding shear (V_y), ultimate shear (V_u), and related mid-span deflection, Δ_{vy} and Δ_{vu}, respectively.

Table 4 The results summary of tested steel beams under shear control

	Temperature	V_y	Δ_{vy}	V_u	Δ_{vu}	Decrease in V_y(%)	Decrease in V_u(%)
Group 1	**Normal**	40.0	-3.46	40.0	-3.46	0	0
	200 C	35.09	-3.69	35.4	-3.92	12.3	11.5
	400 C	30.1	-4.01	32.03	-4.73	24.8	19.9
	600 C	22.75	-3.3	25.0	-6.0	43.1	37.5
Group 2	**Normal**	100.0	-2.2	100.0	-2.2	0	0
	200 C	86.09	-2.25	86.89	-2.3	13.9	13.1
	400 C	52.0	-1.5	76.0	-5.0	48.0	24.0
	600 C	40.9	-1.6	68.0	-12.4	59.1	32.0
Group 3	**Normal**	160.0	-4.02	160	-4.02	0	0
	200 C	138.2	-4.3	140.01	-3.8	13.7	12.5
	400 C	100.8	-3.2	126.7	-8.18	37.0	20.8
	600 C	60.8	-2.0	113.6	-25.87	62.0	29.0

Shear strength was also affected greatly by fire exposure and the reduction reached also to about 38% and all sizes of beams are affected in the same manner. The sudden failure in beams at room temperature was noted clearly by all the groups. More detail is shown in Fig. 7 for the shear strength of steel beams under Group 1. Generally, the drop in shear strength was lesser than flexural strength under the fire effect.

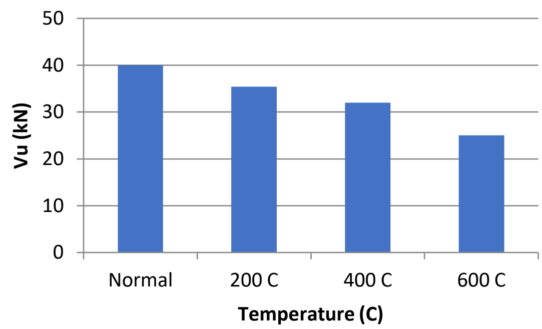

Fig. 7 Degradation of shear capacity with temperature for Group 1 beams.

Also, the change in size and dimensions of the beam has a limited effect on the general response of the beam and the effect of temperature increased at temperature degrees≥ 400 C as shown in Fig. 8.

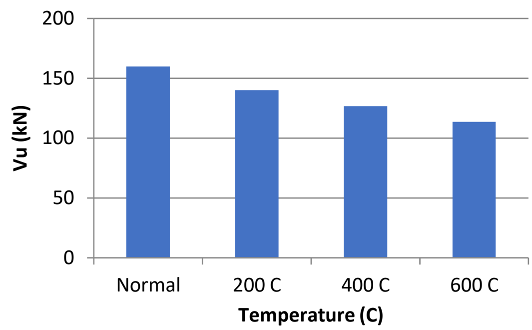

Fig. 8 Degradation of shear capacity with temperature for Group 3 beams.

On the other hand, it noted also that the ductility of the beam increased when the beam exposure to high-temperature levels. These increases were noted at yield and ultimate stages of loading and proportional to the temperature degree, especially at high values. Fig. 9 explains the relation between yield deflection and temperature value of Group 1 specimens.

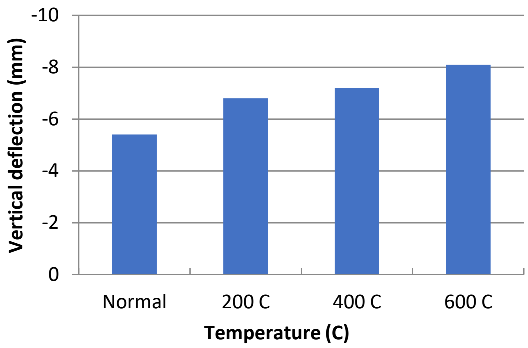

Fig. 9 Deflection at yield strength in Group 1 steel beams under flexural and temperature loading.

At ultimate load, the effect of exposure to fire appeared clearly on the failure deflection of the steel beams as shown in Fig. 10 of Group 1.

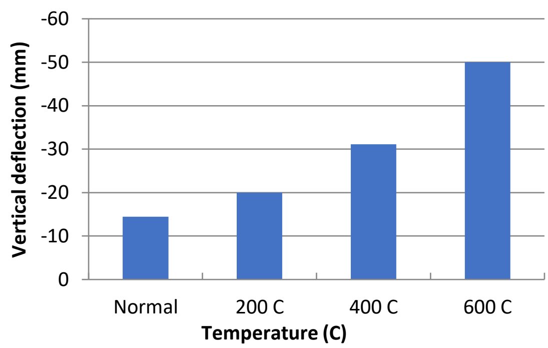

Fig. 10 Deflection at ultimate strength in Group 1 steel beams under flexural and temperature loading.

4.DISCUSSION

The overall behavior of steel beams under the effect of flexural and shear loading at different temperature degrees was reviewed. The most important characteristics of the tested curved will be discussed.

4.1. Specimens under flexural and thermal loading

The load-deflection response of 100 mm height steel beams (Group 1) under flexural and thermal loads was plotted and displayed in Fig. 11 below.

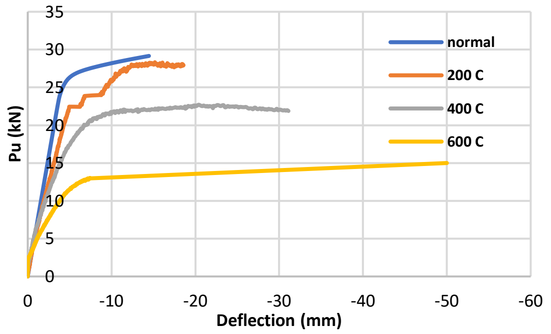

Fig. 11 Load-deflection curves of Group 1 beams under flexural loading.

The figures show the linear behavior of the steel beam under flexural load at room temperature. At the yielding point of steel, the beam enters the plastic range and finally reaches the ultimate load. The strain hardening effect was clear in response to the specimen beyond yielding of material. Exposing the beam to higher temperatures reduced the flexural strength of the beam depending on the temperature rate. As explained in Fig. 11, the response does not change greatly and little drop was noted in yield and ultimate load. A large effect of temperature increase starts at 400 C and beyond. The flexural response of the specimens under Group 2 was displayed in Fig. 12 concerning flexural force vs. mid-span deflection.

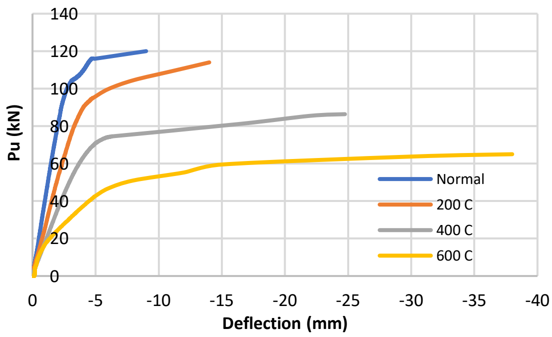

Fig. 12 Load-deflection curves of Group 2 beams under flexural loading.

Specimens of this group have a total depth of 15 cm (i.e 50% larger than that of Group 1). The general response looks to be similar to the beams of Group 1 when the specimens were subjected to flexural and thermal loading. The effect of temperature also appeared clearly at high-temperature values, ≥ 400 C, and the drop in yield and ultimate flexural strength was noted clearly to reach about 46%. However, the response of this group looks to be stiffer than that of lower-depth specimens. When specimens' depth increased by about 100 % (Group 3), the flexural behavior looks to be stiffer than that for other groups, see Fig 13. The yield and ultimate strength were dropped also and the ductility decreased to some extent. The drop in strength reached 37.2% under the effect of flexural and thermal loading.

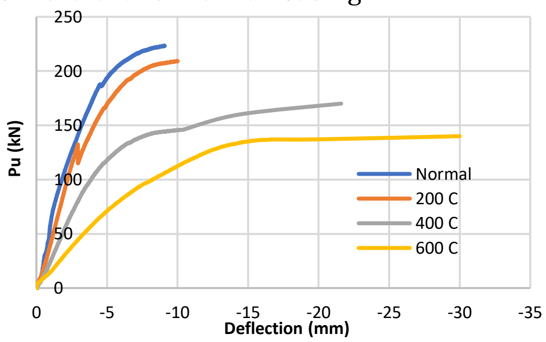

Fig. 13 Load-deflection curves of Group 3 beams under flexural loading.

4.2. Specimens under shear and thermal loading

The shear-deflection behavior of the steel beams under the shear dominant effect (four-point load) for the specimens under Group 1 was explained in Fig. 14 below.

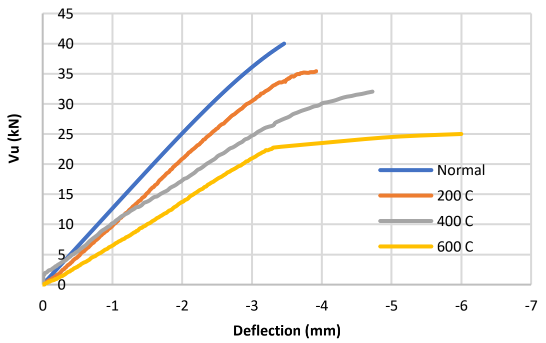

Fig. 14 Load-deflection curves of Group 1 beams under shear dominant loading.

The relation was recorded following vertical mid-span deflection. The sudden failure was noted for the steel beam at room temperature. The reason behind the shear local failure was due to the web crippling under high-stress values. The temperature increase at the critical shear region decreased the shear strength of the beam especially at high-temperature values as explained in Table 4. Local failure of the web is the main reason behind the failure, especially at high temperatures. It noted that, in comparison to the bending effect, the effect of temperature on shear failure appeared clearly at high temperatures (larger than 400 C). The shear strength of Group 2 beams increased due to an increase in web depth as for Group 2 specimens. Fig. 15 explain the comparison between the response of beams under different thermal loading effect. Sudden failure was noted in specimens under room temperature conditions and lower temperature increases.

The nonlinear response appeared in response at high-temperature values due to the web crippling.

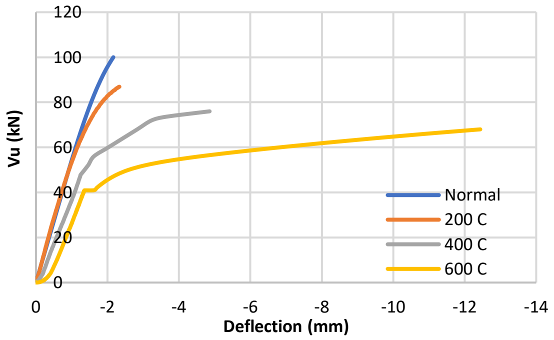

Fig. 15: Load-deflection curves of Group 2 beams under shear dominant loading.

This phenomenon (web crippling) increased with increasing beam depth as shown in Fig. 16 for specimens of Group 3.

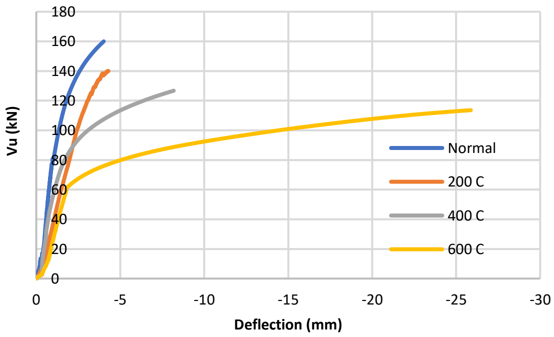

Fig. 16 Load-deflection curves of Group 3 beams under shear dominant loading.

5.COMPARISON WITH AISC EQUATIONS

The equation proposed by the American Institution of Steel Construction (AISC) was detected for the steel beams adopted in the present study at room temperature. As noted in chapter three, the section of the beam was compact and the length was fully braced laterally [15, 16].

5.1. Flexural design equation

The comparison between the experimental and AISC equation curves was explained in Fig. 17. The equation was proposed to calculate the flexural strength of the hot-rolled steel beam under bracing and compact conditions [16].

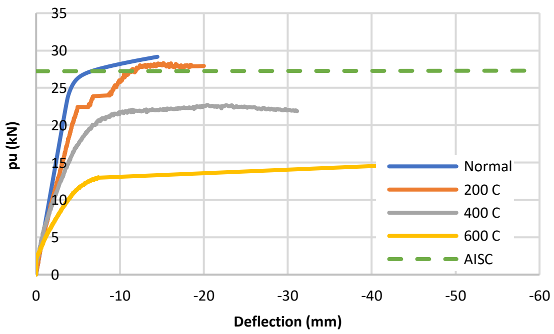

Fig. 17 Comparison of load-deflection curves of Group 1 beams with AISC equation.

It noted clearly that the equation was conservative and underestimated for the behavior of steel beams at ambient temperature. With increasing the temperature degree, the AISC equation deviates from the actual values of the ultimate capacity of steel beams. The same behavior was noted for specimens of Group 2 for the beam at ambient temperature as shown in Fig. 18. The local failure in the web due increase in temperature reduced the strength, then the AISC equation was non-conservative for beams exposed to a high-temperature degree.

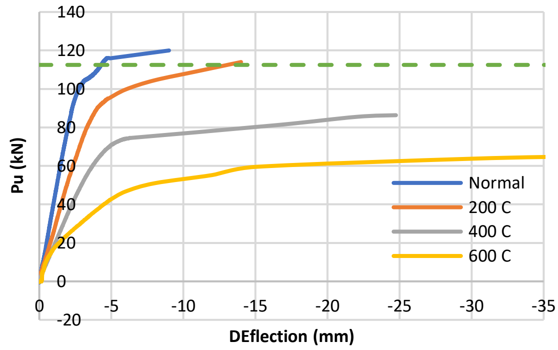

Fig. 18 Comparison of load-deflection curves of Group 2 beams with AISC equation.

Moreover, the specimens of Group 3 were noted also to be unsafe when designed following the AISC equation although these specimens were characterized by deeper depth, Fig. 19.

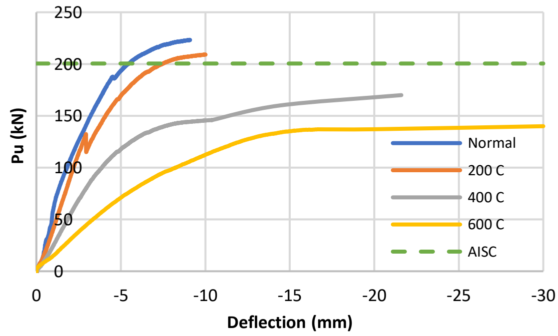

Fig. 19 Comparison of load-deflection curves of Group 3 beams with AISC equation.

5.2. Shear design equation

The shear equation proposed by AISC for the shear strength of I-section steel beams was calculated and compared with the shear-deflection curves obtained in the present study. The basic strength equation is:

$$V_u = 0.6 F_y A_w C_v$$

Where

F_y yield strength, A_w area of the web

C_v ratio of critical web stress to shear yield stress.

For Group 1 specimens (lower depth value), the equation looks to be conservative and gives safety before steel yields as shown in Fig. 20. On the other hand, any exposure to a thermal source reduced the shear strength of the steel beam and the equation looks to be unsafe.

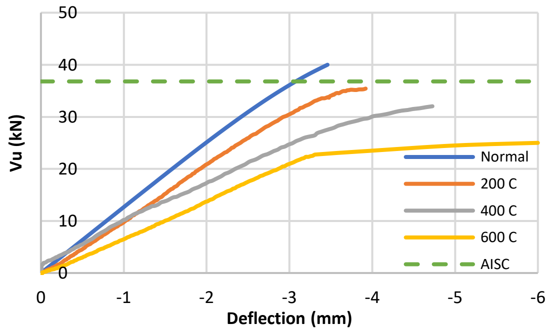

Fig. 20 Comparison of shear-deflection curves of Group 1 beams with AISC equation.

The increase in beam depth (i.e increase in the web area) modifies greatly the shear strength of the steel beams under shear dominant as shown in Fig. 21 and Fig. 22 for specimens in Group 2 and Group 3, respectively.

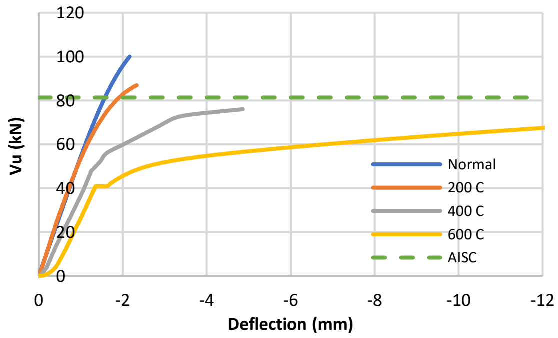

Fig. 21 Comparison of shear-deflection curves of Group 2 beams with AISC equation.

The AISC equation can withstand shear failure at ambient temperature loading and low exposure to thermal degrees. The steel beams failed by shear effect at high-temperature exposure and the failure looks to be gradual.

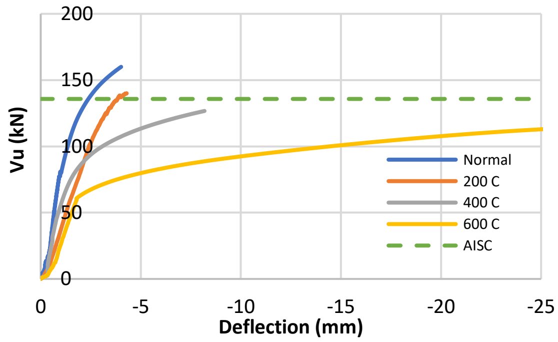

Fig. 22 Comparison of shear-deflection curves of Group 3 beams with AISC equation.

6.CONCLUSIONS

Based on the results obtained from experimental and numerical data, the following conclusions can be drawn:

- There is a lack of research on the thermal stress effect of steel beams under shearing force.
- The temperature rise can lead to rapid degradation of the strength and elastic modulus of steel beams.
- Local web buckling is the main reason for the reduction in shear strength, proportional to beam depth
- The flexural limit state in AISC design may not be conservative where beams are subjected to high flexural and thermal forces. The failure can occur in these cases earlier.

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