Introducing a Novel Diagram-Based Method for Shear Design of Steel Plates at High Temperatures

A. Ghadami[1*], GH. Pourmoosavi[2], A. Ghamari[3]

[1]Assistant Professor, Dept. of Civil Engineering, Azarbaijan Shahid Madani University, Tabriz, Iran
[2]Post Doc. Researcher, School of Civil Engineering, University of Tabriz, Tabriz, Iran
[3]Post Doc. Researcher, Dept. of Civil Engineering, Sharif University of Technology, Tehran, Iran

ABSTRACT

It seems necessary to develop a simplified design approach in order to evaluate the shear strength of web panels under fire condition as the size of furnaces is limited, the cost of experiments aimed at testing the fire resistance of structures is quite high and access to simulation software packages such as ANSYS and ABAQUS is not always guaranteed. In this paper, web panel shear design relationships of AISC360-16 and AASHTO-14 specifications are exploited to be used in fire conditions. To this end, the stress-strain reduction factors provided in EN 1993-1-2 are directly applied. Afterwards, the design curves are proposed for prediction of the ultimate shear strength and limiting temperature of steel plate girders under fire by taking into account the strength degradation caused by high temperatures and the effects due to sectional instability. According to the results, the proposed curves are more accurate in compact plates with plastic shear buckling at both ambient and high temperatures. However, by increasing the web slenderness, the difference is increased. At ambient temperatures, the maximum difference for compact, noncompact, and slender web plates is about 1.1%, 23%, and 28%, respectively. The difference at 400ºC reaches to almost 3% and 7% for non-compact and slender web panels, respectively. In addition, at 600ºC, especially for slender plates, proposed curves yield values that are nonconservative for ultimate shear strength such that the difference is about 11%. Also, the maximum difference for existing experimental and numerical studies is about 20% and 4%, respectively.

KEYWORDS

Fire, plate slenderness, pteel plate girder, shear strength, design diagram.

[*] Corresponding Author: Email: Abbasghadami@azaruniv.ac.ir

1. Introduction

Steel structure and lifespan are affected by fire, and the shear buckling of web panels in addition to failure modes of girders by considering fire as a parameter has been an interesting subject in recent years [1-2]. This has been the primary aim of some studies. It was shown that inelastic or elastic buckling of steel plate webs, that experience plastic buckling at normal temperatures, is a possible phenomenon at elevated temperatures owing to the deterioration of mechanical properties [2], i.e. a change in the failure mode is to be expected.

There seems to be no theoretical research aimed at evaluating the web panel mode change that provides general shear design diagrams of steel plate girders exposed to fire. This study seeks to fill this gap. In this regard, web panel shear design relationships of AISC360-16 [3] and AASHTO-14 [4] specifications are exploited to be used in fire conditions. To this end, the stress-strain reduction factors provided in EN 1993-1-2 [5] are directly applied. Afterwards, the design diagrams are proposed for prediction of the ultimate shear strength and limiting temperature of steel plates under fire by taking into account the strength degradation caused by high temperatures and the effects due to sectional instability. The validation of the proposed diagrams is evaluated by comparing the results with numerical and experimental data.

2. The Proposed Shear Design Diagrams

2.1 Ultimate shear strength at elevated temperature

Based on the direct application of the reduction factors of EN 1993-1-2 [5] for steel stress-strain relationship, the design shear strength of unstiffened web plates at elevated temperatures, $V_{u\text{-}AISC,T}=\phi_v V_{n\text{-}AISC,T}$, shall be determined as Equation 1 with a shear resistance factor of $\phi_v = 0.9$.

$$V_{u-AISC,T} = k_{y,T}.\phi_v\left(0.6\sigma_{yw,20}ht_w\right) \quad for\ \lambda_{w-AISC,T} \le 1.1 \tag{1a}$$

$$V_{u-AISC,T} = \sqrt{k_{y,T}.k_{E,T}}.\phi_v \times\left(0.6\sigma_{yw,20}ht_w\left[\frac{1.1}{\lambda_{w-AISC,20}}\right]\right) \quad for\ \lambda_{w-AISC,T} > 1.1 \tag{1b}$$

$$\lambda_{w-AISC,T} = \sqrt{\frac{k_{y,T}}{k_{E,T}}}.\left(\frac{D}{t_w}\sqrt{\frac{\sigma_{yw,20}}{K_{AISC}E_{20}}}\right) \tag{1c}$$

where $V_{n\text{-}AISC,T}$ is the nominal shear strength, $\lambda_{w\text{-}AISC,T}$ is the nondimensional web slenderness (NWS) parameter at constant temperature. Moreover, $\lambda_{w\text{-}AISC,20}$ is the NWS parameter at 20ºC, and $V_{p\text{-}AISC,20} = 0.6\sigma_{yw,20}ht_w$ is the web plastic shear strength at ambient temperature. Also, $\sigma_{yw,20}$ is the yield stress of web plate at 20ºC, h signifies the overall depth of girder, t_w and D are the thickness and depth of web plate, respectively, E_{20} is the Young's modulus at 20ºC, K_{AISC} is the elastic shear buckling coefficient, and $k_{y,T}$, $k_{E,T}$ are the EN 1993-1-2 reduction factors related to yield stress and Young's modulus, respectively. In this article, similar to the slenderness categorization of plates under the effect of shear loading at ambient temperatures, web panels with $\lambda_{w\text{-}AISC,T}\le1.1$ and $\lambda_{w\text{-}AISC,T}>1.37$ are considered as compact and slender plates, respectively. Also, web panels with $1.1<\lambda_{w\text{-}AISC,T}\le1.37$ are considered to be non-compact plates with inelastic shear buckling failure mode. Therefore, according to Equation 1, Figure 1 can be used to determine the ultimate shear strength (USS) of unstiffened web panels at elevated temperatures in terms of web panel slenderness and steel temperature. As an example, the USS value of plates with $\lambda_{w\text{-}AISC,T}\le1.1$ and $\lambda_{w\text{-}AISC,T}>1.1$ at 600ºC are $V_{u\text{-}AISC,T} = 0.423V_{p\text{-}AISC,20}$ and $V_{u\text{-}AISC,T}=(0.37/\lambda_{w\text{-}AISC,20})V_{p\text{-}AISC,20}$, respectively. Similar figure can be drawn based on the AASHTO-14 [4] relationships as Figure 2.

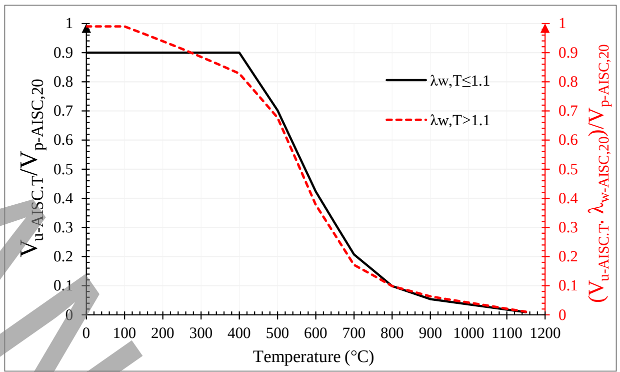

Figure 1. The plate ultimate shear strength variation versus temperature based on the AISC360-16 relationship

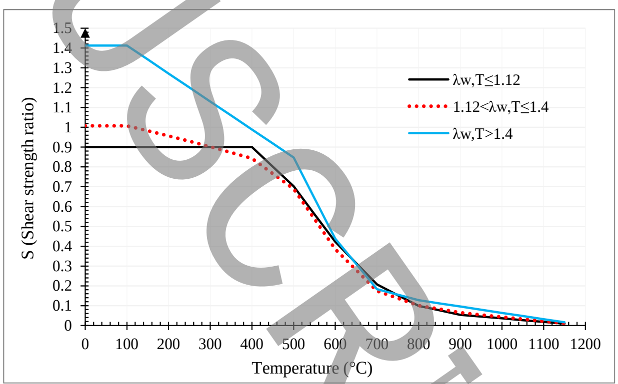

Figure 2. The plate ultimate shear strength variation versus temperature based on the AASHTO-14 relationship

2.2 Limiting temperature

One of the most important parameters needed for understanding the structural behavior is the temperature it takes the structure to collapse. Nonetheless, an evaluation of the residual capacity of fire-exposed components is mandatory before application of load on structures. This helps the engineers with new techniques for adding appropriate structural members in a building or bridge. Therefore, in this section, Based on Equation 1 and given that the NWS parameter at elevated temperatures ($\lambda_{w\text{-}AISC,T}$) is less than or greater than 1.1, the USS reduction factor (R=$V_{u\text{-}AISC,T}$/$V_{u\text{-}AISC,20}$) of a unstiffened web panel can be derived from Fiqure 3 in terms of steel temperature. Similar figure can be drawn based on the AASHTO-14 [4] relationships. As an example, the USS reduction factor belonging to plates with $\lambda_{w\text{-}AISC,T}\leq1.1$ and $\lambda_{w\text{-}AISC,T}>1.1$ at 400ºC, are about 1 and 0.84, respectively. On the other hand, the proposed diagrams in Fiqure 3 can be used to predict the limiting temperature, T_{lim}, at which the panel would fail when a constant shear load is exerted. For example, if, under a loading at ambient temperature, 60% of the shear capacity of a unstiffened web panel with an NWS parameter of $\lambda_{w\text{-}AISC,T}\leq1.1$ is used, the plate will reach its ultimate shear load at a temperature of 560ºC. In other words, at a temperature of 560ºC, this plate will reach its ultimate load by a shear strength reduction of 40%.

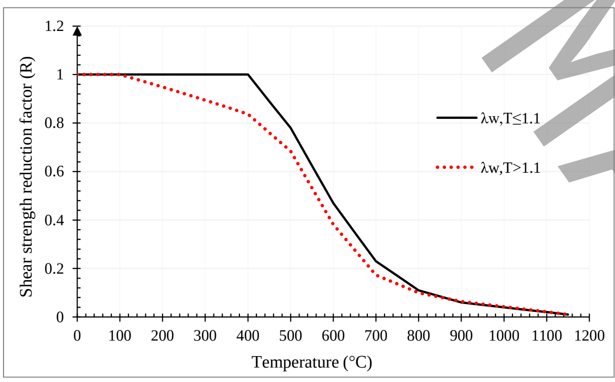

Figure 3. Shear strength reduction factor of the plates versus temperature based on the AISC360-16 relationship

3. Validation of The Proposed Diagrams

The accuracy of the developed method for evaluating the shear behavior of web panels under fire conditions are examined by a comparison with the 1) current paper 54 plate girders with compact, non-compact and slender web panels, 2) the available eight experimental data [6] and, 3) the available four finite element analyses [7]. In this paper, the numerical modeling and analysis are performed using ABAQUS. The S4R element is used for modeling the girders. The modified Riks method is used for the nonlinear static analysis of unstiffened web panels. Loading pattern and boundary conditions of the finite element models are shown in Figure 4.

	Boundary Condition					
Edge	U_x	U_y	U_z	θ_x	θ_y	θ_z
1	0	0	0	0	1	0
2	1	0	1	0	1	0
3, 4	1	0	0	0	0	1
5, 6	1	0	1	0	0	1
7, 8	1	0	1	1	1	1
			0: Fixed			1: Free

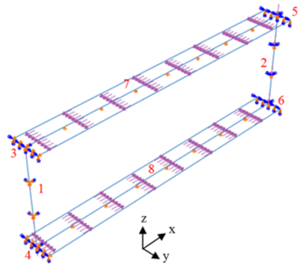

Figure 4. Boundary condition and pure shear loading of models in the finite element analysis

4. Conclusions

In the present work, the ultimate shear behavior of stiffened and unstiffened steel plates was investigated at elevated temperatures. In this regard, shear design relationships of AISC 360-16 and AASHTO-14 specifications were adapted to fire conditions. Next, analytical equations and design diagrams were proposed to predict the ultimate shear strength, failure mode, and limiting temperature under a constant shear load at which the panel would fail. The validation of the proposed diagrams was evaluated by comparing the results with numerical and experimental data. In each section, engineering design examples were also presented. Such assessment is beneficial for developing novel strategies so that structural members can be retrofitted in buildings and bridges.

5. References

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