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Finite Element Modeling of Connections to Concrete-Filled Steel Columns under Fire

Hamid Reza Ashrafi[1], Peyman Beiranvand[2], Mohammad Reza Dadgar[3] and Soroush Dadgar[4]

[1]*Assistant Professor, Department of Civil Engineering, Razi University, Kermanshah, Iran*
[2]*PhD Candidate, Department of Civil Engineering, Razi University, Kermanshah, Iran*
[3]*MSc, Department of Civil Engineering, Islamic Azad University, Abhar, Iran*
[4]*MSc, Department of Civil Engineering , Razi University, Kermanshah, Iran*

Corresponding author's email: Peyman51471366@gmail.com

ABSTRACT: Concrete-filled steel tubular columns have been extensively used in structures, owing to that they utilize the most favorable properties of both of constituent materials, ductility, large energy-absorption capacity, and good structural fire behavior. Concrete inside the steel tube enhances the stability of the steel tube, and the steel tube in turn provides effective lateral confinement to the concrete. Furthermore, the fire resistance of CFT columns is higher than that of hollow steel tubular columns, external protection being not needed in most cases. During a fire, the steel tube acts as a radiation shield to the concrete core and a steam layer in the steel-concrete boundary appears. This paper employs the general finite element software ABAQUS to numerically model the behavior of restrained structural subassemblies of steel beam to concrete filled tubular (CFT) columns and their joints in fire. The simulations were conducted using 3-D brick elements to enable detailed structural behavior to be obtained. For validation, this paper compares the simulation and test results for the three fire tests using reverse channel connection recently conducted at the University of Manchester. This comparison demonstrates that the 3-D finite element model is able to successfully simulate the fire tests. Afterwards, the validated finite element model was used to conduct a preliminary numerical study to investigate the feasibility of changing some of the connection details to enhance survivability of the structure in fire. Specifically, this investigation concentrated on developing connection methods to enable catenary action in the connected beam to be more fully developed. An example is to develop a hybrid flush/extended endplate and flexible endplate connection in which the tension part of the connection uses a flush/extended endplate for increased tensile resistance but the compression part of the connection uses a flexible endplate for improved ductility. It has been found that, without additional cost, using a hybrid extended/flexible endplate connection to replace a flush endplate connection has the potential to enable the connected beam to survive significantly increased temperature.

Key words: Concrete-Filled Steel Columns, Reverse Channel, Finite Element, Endplate.

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INTRODUCTION

The philosophy of using composite materials is that the weakness of one element will be compensated by another element in order to have optimum use from this set. But in recent years, another idea has been added which expresses confinement in addition to the above purpose. Confined structures have more flexibility rather than concrete structures and yet they are stiffer and in conclusion, they have less capacity for buckling than steel structures. Concrete-filled steel sections is a special type of composite sections of steel and concrete that contains foursquare or circular sections with thin thickness in outside and concrete in inside. Presently, the behavior of connections under the effect of fire is one of the most important goals in conducted researches in the field of structural strength against fire. But owing to being costly and time consuming of laboratory studies, most researches have been carried out on the basis of modelling. For instance, Liu examined the behavior of steel structures' connections under temperature increase by using finite element model. Also, Al-Jabri et al. (2005) investigated the behavior with balanced endplate under the effect of fire. Sarraj et al. (2007) surveyed the three-dimensional finite element model of steel structures' flange connection under the effect of fire. Hou et al. (2008) by three dimensional finite element model examined the behavior of steel structures' connections through using flexible endplate under the effect of temperature increase. In this paper, the validation of the results of modelling will be done by Wang and Ding's laboratory results. In this experiment, connection of concrete-filled steel columns into steel beam have been performed by connecting reverse channel, and by using extensive, flexible and balanced endplate, in figure 1 there is a sample of this connection with flexible endplate.

In this article works on examination of various methods for modelling finite element of this type of connection through concrete-filled steel columns under the effect of fire, and also effective parameters on increasing strength connection are investigated.

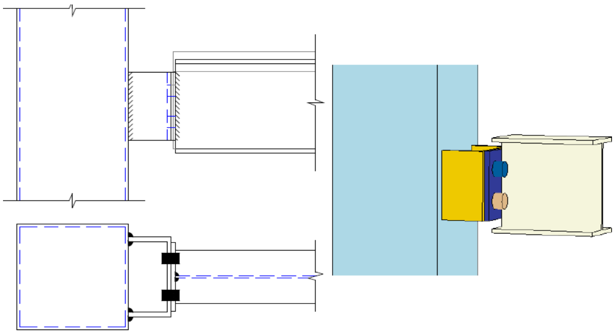

Figure 1. Reverse channel connection with flexible endplate

MATERIALS AND METHODS

Explanation of Wang and Ding's test

The most important purpose of this test is gathering experimental results to determine the temperature of connection region and structural operation of connections and structure against fire. In first 8 tests from 10 tests, the beam was affected by loading and temperature increase simultaneously, that the behavior of steel beam during getting warm and the behavior of beam in getting cold phase in two other test by keeping the conditions of loading are investigated. In all tests, steel beam which has been located on two concrete-filled steel columns are affected by equal standard thermal conditions, that in figure 2 the general scheme of Wang and Ding's test has been displayed.

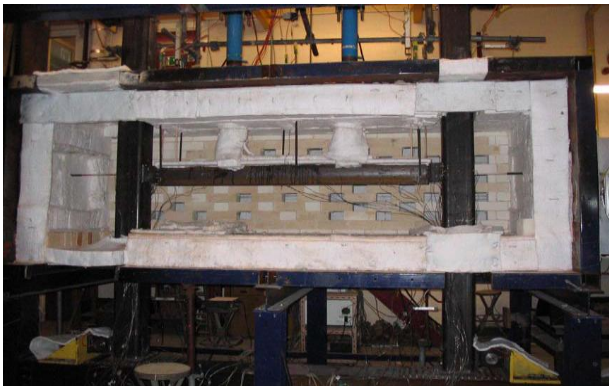

Figure 2. General scheme of Wang and Ding's test

The size of beams' sections are similar in all tests and equals 178×102×19 UB. In 7 tests, square section with dimensions of 200×200 millimeter has been used and in other 3 tests, circular section with diameter of 193.7 millimeter has been used and for connections, 8.8 screws with diameter of 20 millimeter has been applied. The upper flange of beams with ceramic cover of 15 millimeter thickness will be heated by thermal source. Like figure 3, the end of columns are clamped against lateral movement but they have free movement longitudinally. The beam loading in two points of beam are performed by separated jacks.

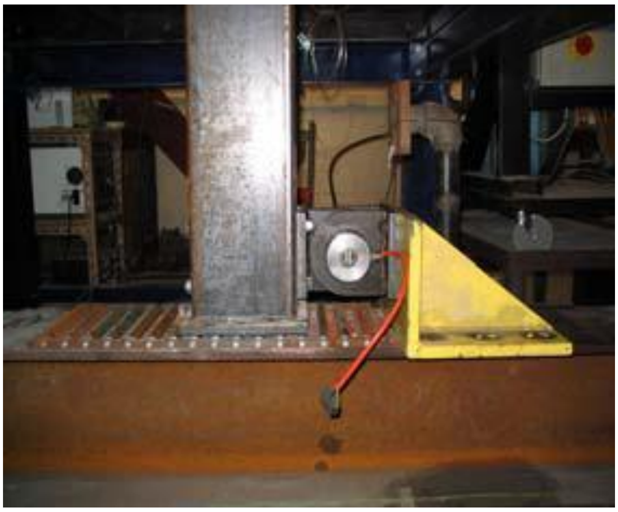

Figure 3. The clamped scheme of end of column in Wang and Ding's test

The effect of temperature increase on concrete and steel properties

The mechanical and thermal features of steel and concrete are totally different, however by increasing temperature, strength and stiffness of both of them decrease. In figures 4 and 5, the stress-strain curves of steel and concrete for normal temperature (20º C) has been represented as T20. For all sections used in this article, the yield stress (f_y) equals 350 Newton per square millimeter, elasticity modulus (E_s) is 21×10^4 Newton per square millimeter, compressive strength (f_c) equals 30 Newton per square millimeter and strain (ε_c) is 0.0025. The stress-strain curve of steel under the effect of heat increase has been drawn according to BS EN 1993-1-2 code and for concrete has been formed based on BS EN 1994-1-2 code.

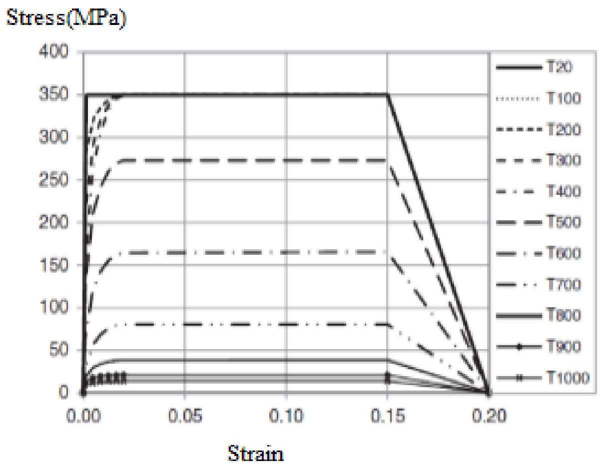

Figure 4. Stress-strain curve of steel under the effect of heat increase

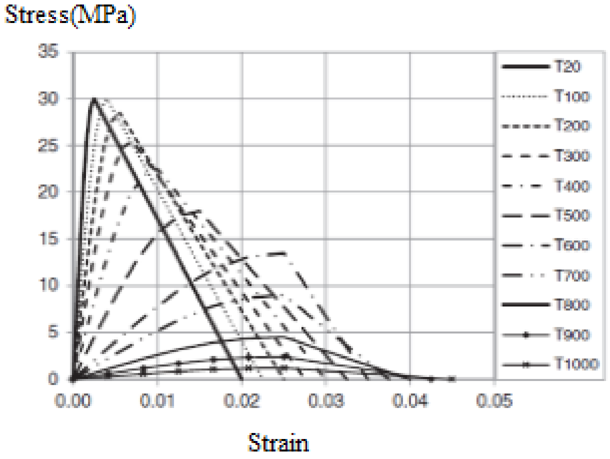

Figure 5. Stress-strain curve of concrete affected by heat increase

For simulating by Abacus software, steel will be modelled on the basis of real stress-strain relation of equations 1 and 2.

$$\sigma_{true} = \sigma_{nom}(1 + \varepsilon_{nom}) \quad (1)$$

$$\varepsilon_{true} = ln\,(1 + \varepsilon_{nom}) \quad (2)$$

In which ε_{nom} and σ_{nom} are nominal strain and stress of section, respectively. The values of real stress and strain of steel has been given in table 1.

For modelling concrete in plastic region and examination of deterioration in it, the plastic damage model of concrete has been used. The values of stress, strain and plastic destruction of concrete in tension and compression has been demonstrated in tables 2 and 3.

Table 1. The values of real stress and strain of steel

Real stress (mega Pascal)	Plastic strain
300	0.000
350	0.025
375	0.100
394	0.200
400	0.350

Table 2. Values of stress, strain and plastic destruction of concrete in tension

Tensile strength (mega Pascal)	Fraction strain	Destruction parameter in tension
5.30	0.0	0.00
5.31	0.000176	0.25
0.58	0.001539	0.99

Table 3. Values of stress, strain and plastic destruction of concrete in compression

Compressive strength (mega Pascal)	Fraction strain	Destruction parameter in compression
17.5	0.000000	0.000
25.7	0.00038	0.112
34.9	0.00189	0.429
35	0.00218	0.466
28	0.00456	0.701

Description of used section

First, we introduce the structural model and used connections in numerical simulations. Figure 6 shows the structural model which is simulated by Abacus software.

For modelling in Abacus, five types of connections have been used:

1 – Connection with flexible endplate

2 – Connection with balanced endplate

3 – Connection with extensive endplate

4 – Connection with flexible balanced endplate

5 – Connection with flexible extensive endplate, that these connections have been shown in figures 7 to 11.

In reverse channel connections, screws must have required strength to prevent fracture of connections under the effect of tensile and bending loads. In this study, screws of type 8.8 and 10.9 with diameters of M20, M24 and M27 have been used to examine the strength effect of screw.

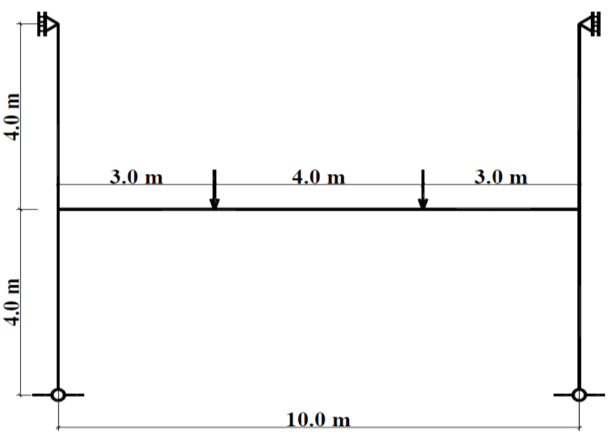

Figure 6. Simulated structural model in Abacus software

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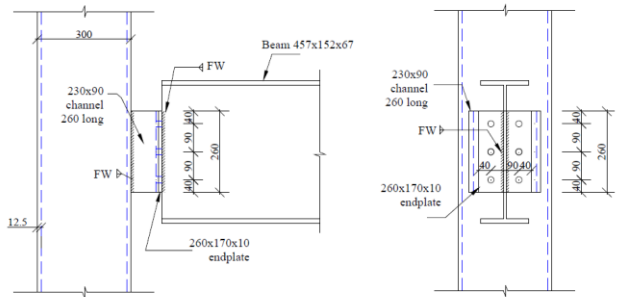

Figure 7. Connection with flexible endplate

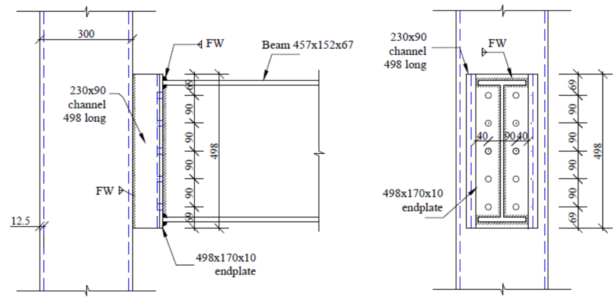

Figure 8. Connection with balanced endplate

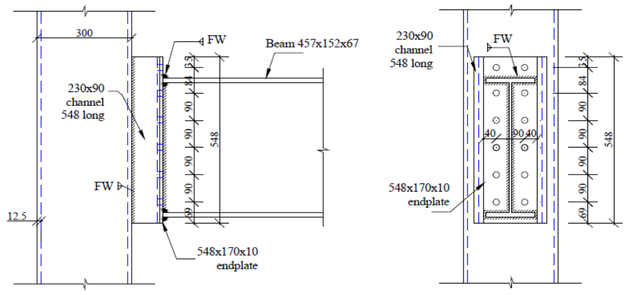

Figure 9. Connection with extensive endplate

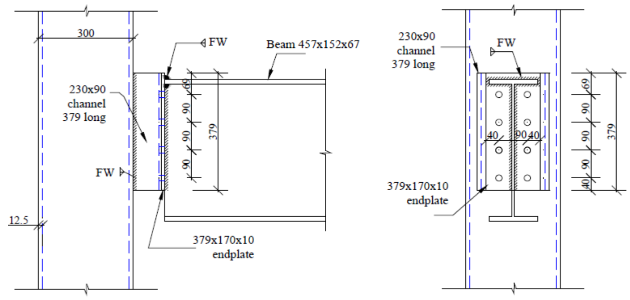

Figure 10. Connection with flexible balanced endplate

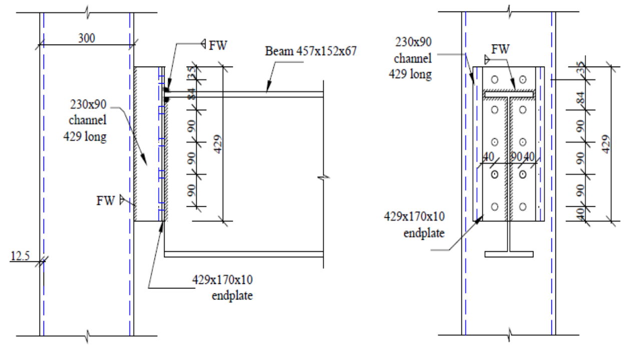

Figure 11. Connection with flexible extensive endplate

Normal simulation by abacus software

First, the connection of concrete-filled steel columns to steel beam will be modelled by using a reverse channel in Abacus software like figure 12.

Plastic analysis includes three main parts: stress-strain curve, yield criteria and stiffening law. Stress-strain curve for structural elements has been shown in second part of this paper. For modelling the behavior of materials, Fon-Misez yield criteria and isotropic stiffening law have been applied.

In this model, the issues relevant to geometric nonlinear analysis were also considered and great deformation method has been used. The analysis method was Newton-Rofson software and due to contact elements between steel and concrete and regarding friction of contact surfaces, asymmetric Newton-Rofson method were utilized.

Concrete core is defined by a six-sided, eight- node element with three transitive degree of freedom in each node and by C3D8R model. Materials are of concrete type with capability of fraction in three orthogonal directions under the effect of tension and failure affected by compressive stresses and plastic deformations too.

Steel wall is described by C3D8I element which as well as C3D8R model is defined with eight nodes and three degree of freedom in each node and it has suitable agreement to other used elements in model. In addition, friction and slip between steel and concrete core are modelled by surface to surface contact element. This element is able to transfer compression in the normal direction and shear in direct tangent to the surface.

Moreover, to investigate the behavior of column after buckling and passing from critical point such that it shows reduction in bearing capacity without divergence in solving problem, arc length method has been used for nonlinear equations.

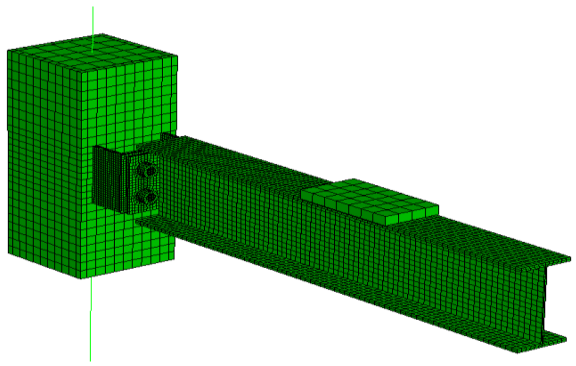
Figure 12. Connection finite element model

Effect of numerical modelling on results

In this part, the effect of change in some parameters on numerical results are examined. These parameters include: mesh size, yield stress of steel, empty space between screw and plate and lateral and torsional fixing in 4 corners of loading plate.

Mesh classification size of model

The smaller the size of mesh classification is, the more time is needed to analyze the model, while if the size of mesh get bigger, it cannot be able to specify the buckling properties of many important elements. Therefore to prevent sudden buckling of web, a thickness of two layer element must be used for web section.

In figures 13 and 14, the obtained results for proper and coarse mesh classification is compared with the results of test 4, for axial force and displacement in the middle of beam span by connection of reverse channel. As we see, the results of proper mesh classification have high accordance to laboratory results.

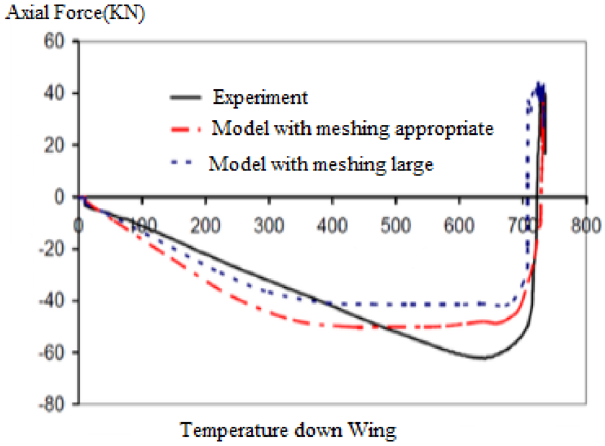

Figure 13. Comparison of axil force of beam by various mesh classification

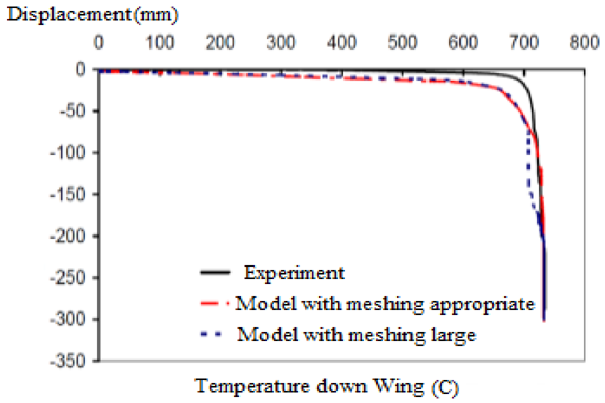

Figure 14. Comparison of axil force of beam by different mesh classification

Effect of steel yield stress increase

In numerical modelling, average yield stress, allowable stress and elasticity modulus of test has been used for steel members in standard temperature and yield stress is used in the range of 275 to 350 Newton per square millimeter.

Besides, the obtained results have been compared to laboratory results for axial force and beam displacement according to the temperature of lower flange of beam with yield stress of 275 and 350 Newton per square millimeter, as in figure 15 and 16.

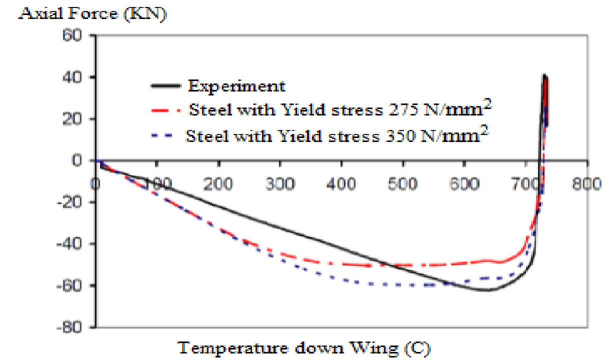

Figure 15. Comparison of axial force of beam with various yield stress

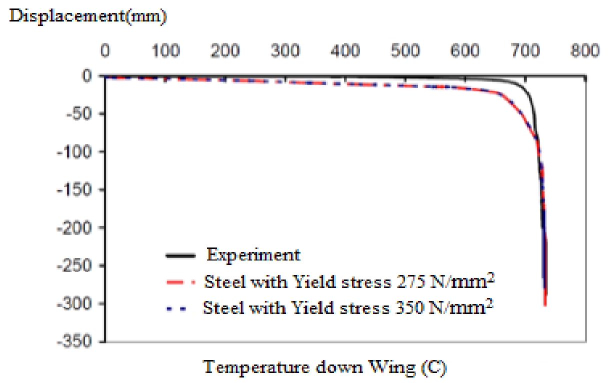

Figure 16. Comparison of beam displacement with different yield stress

The effect of empty space between screw and endplate

In Abacus software to reduce calculation time, all contact surfaces have been modelled with surface to surface contact method and by decreasing slip effect. Also, the friction coefficient has been considered 0.3 and allowable looseness between screw and hole equals 1 millimeter for all models. The effect of empty space between screw and plate has been investigated for all models and in figures 17 and 18, numerical results for axial force and deformation in the middle of beam span in two modes with looseness and without looseness of 1 millimeter have been compared with test results. As it is seen, in the stage of beam thermal expansion, increase of looseness between screw and plate leads to significant decrease in compressive force, whereas deformation does not change much in the middle of beam span.

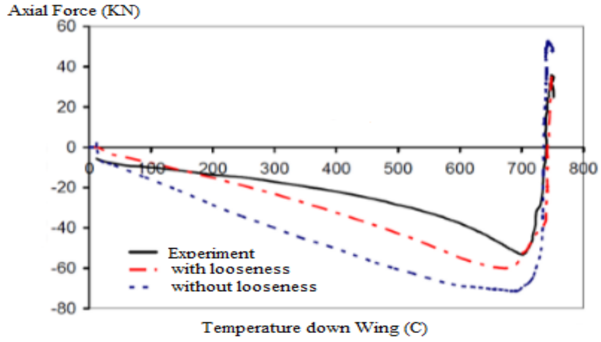

Figure 17. Comparison of beam axial load with looseness of different screw

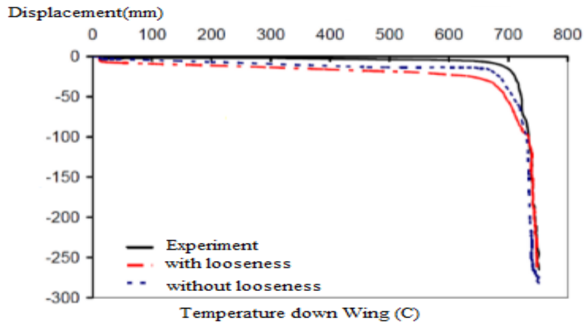

Figure 18. Comparison of beam displacement with looseness of different screw

Effect of lateral torsional fixed end

In figures 19 and 20, numerical results for axial force and deformation at the middle of beam span in two modes of fixed end and without lateral torsional fixed end have been compared with the test results and the conclusion is that numerical results for the mode of lateral torsional fixed end loaded at the four corners of plate have high agreement with laboratory results. It is observed that in thermal expansion mode, by increasing compressive load the results for fixed end and without fixed end coincide with each other up to a definite temperature, but from then on they have considerable difference.

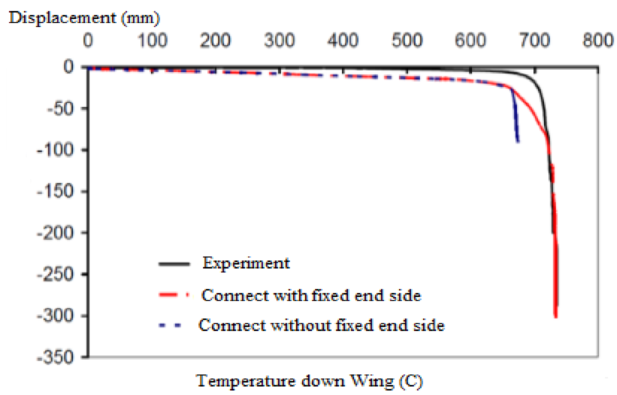

Figure 19. Comparison of beam axial force with various fixed end

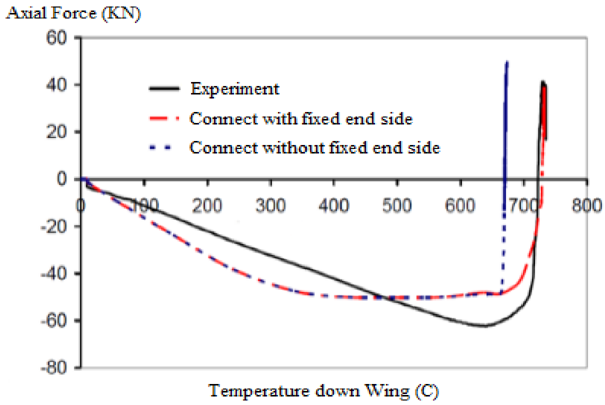

Figure 20. Comparison of deformation at the middle of beam span with different fixed end

Effect of endplate type on results

In figures 21 and 22, we work on the comparison of the effect of connection types on axial force and displacement at the middle of beam span, the connections include connection with flexible endplate, extensive endplate, flexible extensive endplate, and flexible balanced endplate.

As it is observed in figure 21 due to increase of little stiffness in connections with extensive balanced endplate in proportion to other connections, beam compressive force will have little increase during thermal expansion. Moreover, in these two types of connection, because of more buckling capacity rather than other connections, they have more rotational stiffness and therefore, connections with extensive endplate and with flexible extensive endplate have better performance than other connections and use of connections with balanced and flexible balanced endplate do not have much difference in tolerated temperature increase by connection. Also in figure 22, the displacement of middle of beam span in connection types have been compared, as it is seen the maximum sustained temperature by beam depends on strength and ductility of connections.

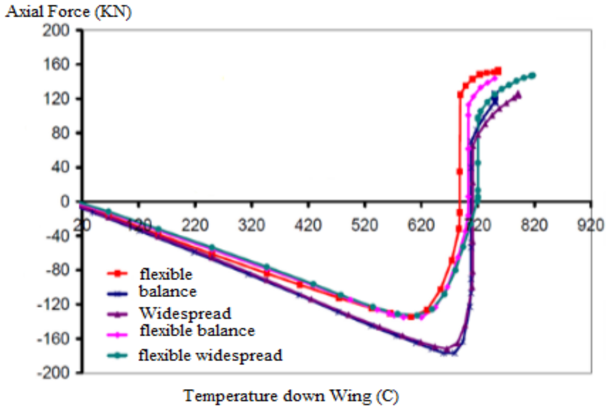

Figure 21. Comparison of beam axial force in connections with different endplate

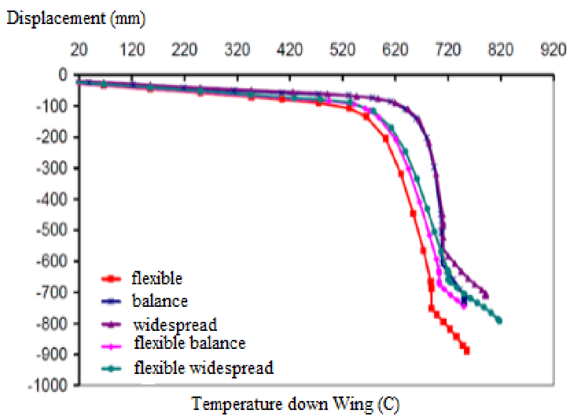

Figure 22. Comparison of displacement in the middle of beam span in connections with various endplate

DISCUSSION AND CONCLUSION

Use of connections with flexible endplate in phase of getting cold increases the possibility of failure, although the probability of this failure can be reduced by increasing the thickness of reverse channel web and use of ductile steel.

Among the five investigated connections in this study, connections with extensive endplate and connections with flexible extensive endplate have the best performance against fire and connections with balanced and flexible balanced endplates are not so effective.

In thermal expansion stage of beam, increasing looseness between screw and plate leads to significant decrease in compressive force while deformation in the middle of beam span does not change much.

Use of steel with yield stress of 275 Newton per square millimeter for endplate and reverse channel have high agreement with the laboratory results in standard temperature.

In connections with extensive, flexible and extensive flexible endplate affected simultaneously by tension and bending moment in screws, failure happens and in connections with balanced and flexible balanced endplate, failure occurs in the web of channel in screw region and also in the corner of channel web near to flanges usually happens.

Failure in reverse channel and endplate can be postponed by increasing their thickness. Of course, increasing dimensions and thickness should be subject to fulfil the conditions of codes.

In thermal expansion mode, by increasing compressive load up to a definite temperature the results match each other for modes of fixed end and without lateral fixed end but from then on they have considerable difference.

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