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A NUMERICAL STUDY ON SEISMIC BEHAVIOR OF STEEL JOINTS EQUIPPED WITH CURVED DAMPERS

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Abstract- Recently, controlling the response of structures through input energy absorption and dissipation in times of earthquake has been detected. One of the common energy absorption systems is the metal dampers used to improve the earthquake performance of the structures. These dampers behave based on flow property. The metal damper flows whenever pressures generated in the damper are greater than the yield stress of the metal materials. This way, a fraction of the input energy is dissipated on the curved damper and the resulting damage in the members of the frame structures is reduced. The curved metal damper is a type of flowing metal damper has been studied in this paper. These dampers have simple geometry and are fabricated by cutting steel sheets. These dampers dissipate the input energy to the structure through bending yield. The curved metal dampers are modeled using finite component software, Abaqus. Then, the effect of various geometric parameters of the curved metal dampers on their performance under heat loading is studied. Results show that by increasing the length of the curved metal dampers, the values associated with initial hardness, resistance, and energy dissipation capacity of the dampers are reduced. On average, these parameters are reduced by 31.45%, 24.2%, and 34.1%, respectively. As the depth and the thickness of the curved metal dampers increase, their behavior improves and the values associated with their initial hardness, resistance, and energy dissipation capacity are increased. Overall, these parameters increased by 50.4%, 47.61%, and 31.25%, respectively.

Keywords: Steel Joints, Curved Damper, Heat Loading.

1. INTRODUCTION

So far, earthquakes are one of the most destructive natural disasters, which cause so many human and financial losses because predicting the exact time and place of their occurrence is impossible. Experiences obtained from severe earthquakes show that structures relying only on traditional seismic systems cannot perform appropriately against strong earthquakes. Traditional seismic design of the building structures is based on the plasticity of the structural members to provide dissipation capacity for input energy of an earthquake. In times of severe earthquakes, this design allows the structural members to enter non-elastic regions and absorb and dissipate input energy to the structure. In this way, the main members of the frame like the beam in bending frames, divergent bracing, and linked beam in divergent bracing frames plastic hinge is formed.

Considering their proper plasticity, steel bending frames are usually used in the seismic design of structures. However, these structural systems have a low hardness that may result in irreparable damage to them because of large displacements of the structure. Also, investigating the damages in the bending frames after strong earthquakes reveals breakdown and rupture in beam-to-column joints followed by damage to the main elements of the structure [1].

One of the approaches used in modern seismic design of the structures is increasing their damping to dissipate input energy and reduce the seismic response of the building. As a new seismic design method of the structures, using the same dampers as energy dissipation systems could be mentioned [2]. These systems can concentrate energy dissipation in predefined regions and reduce the nonlinear behavior of the main structural members of the frame, which deal with gravity-bearing tasks. So, the possibility of damage to the main structural members is reduced, too. Now, utilizing passive energy dissipation in the structures is known as an effective and fairly inexpensive method to reduce earthquake damage. This dissipation could be based on different mechanisms; inelastic deformation of plastic metals like steel in metal dampers, friction slips in friction dampers [3], fluid passing through narrow apertures in viscous dampers, deformation of the viscoelastic materials in viscoelastic dampers could be mention as some examples.

To achieve an economic seismic-resistant design, the energy absorption and dissipation of the structures must be considered. In recent years, many researchers have proposed various techniques to increase the energy dissipation capacity of the structures based on the flow property of the metals. Metal dampers are considered one of the most common energy dissipation systems. They are used to control and reduce the seismic response of the structures in times of earthquakes. These dampers operated based on the flow properties of the metals. Whenever applied forces on a damper are greater than its capacity, the metal damper flows. This way, by plastic deformation, the damper absorbs the input energy to the structure and prevents damage to the main members of the frame [4].

The choice of design parameters for this type of damper has a considerable effect on the nonlinear behavior of the structures. As the metal dampers do not require complicated technology for fabrication, they have lower implementation and maintenance costs in comparison to other systems.

Also, the lower impact of the environmental conditions (like temperature, humidity, and etc.) on their mechanical systems are of much importance in the seismic design of the structures by improving the existing building. Considering the aforementioned reasons, in regions with potential seismic construction such as Iran, studying the performance of the energy absorption systems like metal dampers is crucial. Fire resistance of beam-to-column joints is very important in the design of steel bending frames. Quantifying the effect of heat loads on beam buckling, displacement, rotation, hardness of the joint, and anchor-of-rotation behavior for temperatures from 20 to 900 degrees centigrade is performed. Results show good performance for screw end sheet joints in terms of high resistance and low breakdown in comparison with three other joint types [5].

Previous studies in recent decades have investigated the fire behavior of typical screw joints. However, few studies have investigated the behavior of screw joints with high-resistance screws exposed to fire. This study includes a series of numeric analyses to investigate the behavior of two screw joint types, i.e., expanded screw end sheet joints and beam-to-column screw sheets exposed to fire with and without preloading. Different parameters like the thickness of the joint sheet will be investigated. Also, this study investigates a numeric method for damage index parameters using an explicit dynamic solver and breakdown modes, deflection along the aperture, displacement of the beam, and the axial forces resulting from the fire in detail. Results show that preloading on screws has no substantial impact on the response of the end joint sheet exposed to fire, and the behavior of beam to column joint sheet exposed to fire depends on the thickness [6].

A numeric analysis is evaluated using Abaqus, on high-resistance metal end sheet joints exposed to fire. Results of numeric modeling by using anchor-rotation equation, breakdown mode, and the pattern of yield line of the joint show acceptable accuracy compared to experimental results. It provided an efficient, economic, and accurate tool to study the performance of the high fire resistance steel joints. Hence, this numeric analysis method can be used with high reliability for predicting the behavior of high fire-resistance steel joints with maximum anchor under different fire conditions and various environment temperatures [7].

In 2017, Hsu and Halim proposed and designed a novel metal damper called curved metal damper. They equipped several one-floor frames and a metal aperture with the curved metal dampers and tested under cyclic loading. These dampers were installed in the beam-to-column joint region of the steel frames. After adding the curved metal dampers to the steel frames, their performance was improved [8]. In their next experimental study in 2018, curved metal dampers were used in the bracing metal frames [9, 12].

Structural fire resistance is defined as the characteristic of a building for fire resistance and protection [10, 13]. There are two issues to define fire resistance.

The first issue is the ability of a member to maintain structural strength and stability when exposed to fire. The second one is for some members such as walls and ceilings that prevent the spread of fire. Fire resistance is typically achieved by placing a sample under a standard test [10]. The result of the test is called the degree of durability against fire in hours. It is obtained based on the time that takes for the sample to meet the accepted criteria in the experiment.

The degree of fire resistance required for different components of the building is given in the regulations, which depends on the type of use, number of floors, and floor area. Regarding the standard test being a comparative test and not a predictor of actual behavior, the degree of resistance to laboratory fire to estimate how long a member cannot be destroyed in a real fire cannot be used. In general, the degree of fire resistance of a structural member is a function of:

- The volume of applied heaviness to the part
- Type of part (beam-column, etc.)
- Dimensions of the part and support situations
- The heat current from the fire around the part
- Type of substantial (steel concrete, etc.)
- The effect of growing the temperature of a structural part on the mechanical properties of its component.

The behavior of a structural member in a fire depends on the mechanical and thermal characteristics of that member. As the temperature increases, the resistance of the member to a certain deformation decreases the coefficient of elasticity and stiffness [10].

The curved metal damper investigated in this research is one of the different types of submersible metal damper. The reason for naming these dampers is the geometry with the curvature of their steel piece. These attenuators dissipate the energy entering the structure by absorbing energy and performing inelastic deformations. There is no need for advanced technology to make curved metal dampers because these dampers have a simple geometry and are made by cutting steel sheets according to the required dimensions. So, the speed of manufacturing and installing curved metal dampers is high. Curved metal dampers can be used in the seismic design of steel structures by reinforcing existing buildings.

The geometric details of the curved metal damper are shown in Figure 1. As shown in the figure, there is a gap between the direction of application of the axial load $(P\Delta)$ and the damping center, which is called decentralization (Δ). Due to the effective geometric structure of curved metal dampers, when these dampers are subjected to axial force, due to the deviation of the axial force from the center of the curved metal dampers, an additional bending anchor is created in them.

According to the above, the behavioral mechanism of curved metal dampers is of the bending yield type. In other words, when they are subjected to reciprocating loading, the receiver behaves flexibly and the curved metal dampers are compressed and stretched. These dampers can be installed at the connection of the beam to the column.

By predicting the concentration of noise in curved dampers, they act as a fuse in the building and reduce the nonlinear behavior of the main members of the frame by deforming the plastic. If the connection of the curved metal damper to the structure is of the screw type, after the earthquake, in case of failure, they can be repaired or replaced at a lower cost.

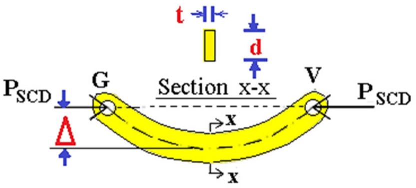


Figure 1. Details of the Geometry of the Curved Metal Damper [9]

2. METHODOLOGY

To evaluate the effectiveness of curved metal dampers on the improvement of the performance of steel connections, a steel connection of single-span, the single-story rigid connection was modeled in the environment of Abaqus software. In the steel connection of the beam and column sections, with a box 300×10 mm specifications have been selected from the box sections.

The angle L15×150×10 mm was used for the connection of beam-to-column. The studied models include a steel connection with rigid connections without any damper and one steel connection with rigid connections with a curved metal damper. Both connections have a length of span and a height of 2000 mm. Figure 2 presents the dimensional characteristics of steel connections. It should be noted that the solid element in Abaqus software has been used to model the beam, column, and curved damper.

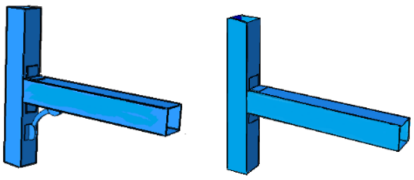


Figure 2. The dimensional characteristics of steel connection with curved metal damper [11]

The length of curved metal dampers in this study is equal to 400 mm. The depth and thickness of the curved metal dampers were selected equal to 80 mm and 30 mm, respectively.

The angle between the two ends of the curved damper was also equal to 90 degrees. The names of models were selected according to the selected geometric parameters for the curved dampers. All the curved metal dampers were modeled using finite element software Abaqus and were analyzed under thermal loading. Steel ST37 with the yield stress of 240 MP and the ultimate stress of 370 MP was used in the modeling of the curved dampers. Also, the elasticity module was selected equal to 210 GP and the Poisson ratio was equal to 0.3. The protocol of the thermal loading applied to the dampers can be observed in Figure 3.

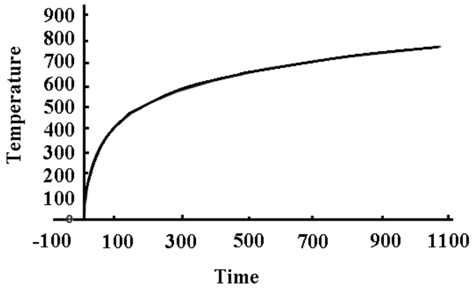


Figure 3. Thermal loading applied to the curved dampers [11]

The tie will be used to connect or weld the damper to the connection plate, and the load of gravity in the first step and the heat load in the second step will be used for loading. The details of loading and how to introduce the interaction between different parts of the connection are given in Figure 4.

The meshing has been performed individually for each segment and we use "structure" mesh for the meshing of the intended model due to its meshing accuracy and "C3D8R" mesh for the elements of the model. The size of meshes for beam, column, and joints is 4 cm. The size of the mesh for the modeling of curved dampers was considered equal to 2 cm due to its sensitivity. The details for the meshing of the intended joints are shown in Figure 5.

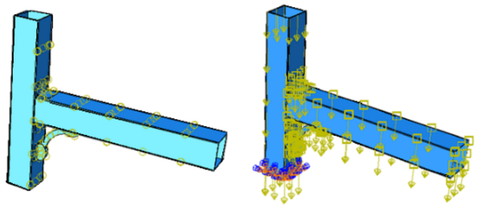


Figure 4. Introducing the loading and interaction between different parts of the connection [11]

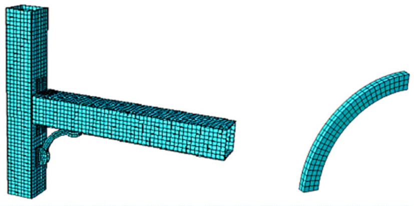


Figure 5. The Meshing of the intended joint [11]

2.1. Confirmation

For validation, the article of Navid Siahploo, et al., Who investigated the behavior of heat-treated steel joints in 2014, has been used. The model consists of a vertical column and a planar beam the height of the column is 2.85 meters and the length of the beam is 2.7 meters.

The cross-section of the connection beam is IPE300 and the cross-section of the connection column is 300 HEA. Figure 7 shows the cross section of the beam and column that is used. The screw connection specifications with the end plate are shown in Figure 8. Figure 9 shows a comparison between deformations created in the junction region for the laboratory sample and the finite element model of paper and simulated finite element model.

Figure 10 compares laboratory results and numerical analysis of displacement diagrams over time. It is observed that the displacement-time curve for connection corresponds well with the test results in the elastic and plastic range.

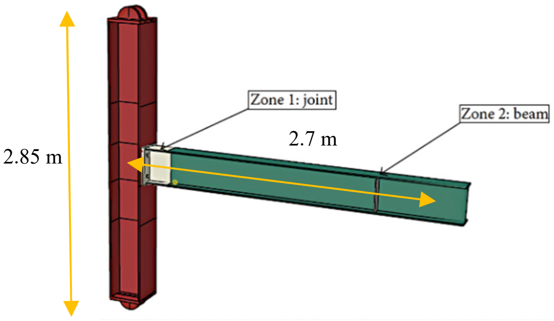
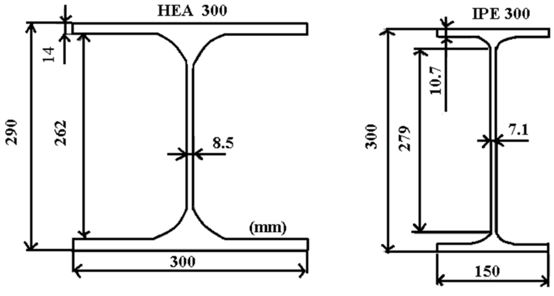


Figure 6. General and specifications of the reference sample [11]



(a) (b)

Figure 7. Geometric characteristics of beams and columns, (a) cross-section of the beam and (b) cross section of the column [11]

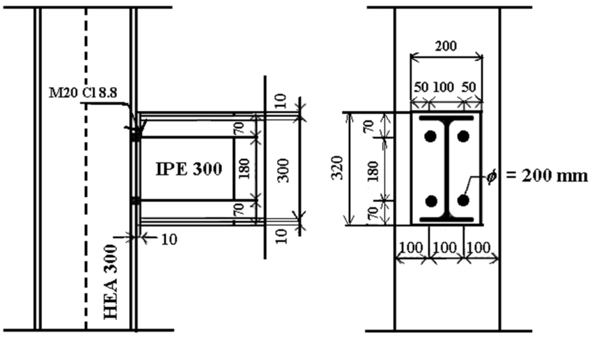


Figure 8. Screw connection specifications with the end plate [11]

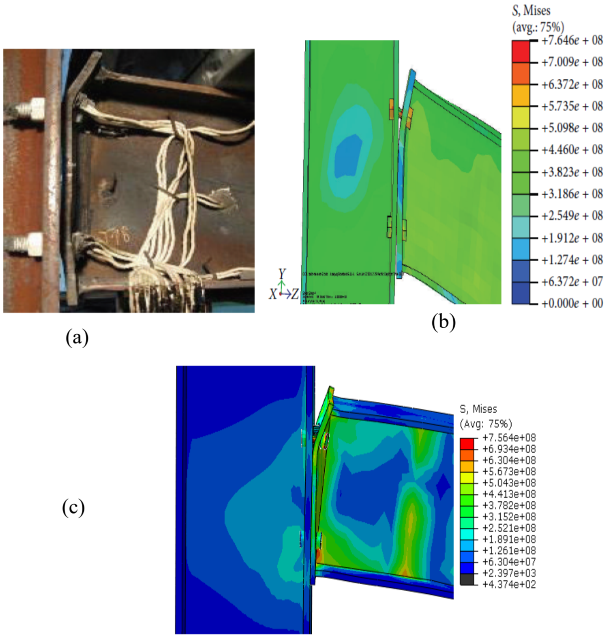


Figure 9. Correspondence of results related to stresses and location of failure in connection: (a) Reference laboratory sample; (b) the finite element model of the reference paper; (c) finite element model [11]

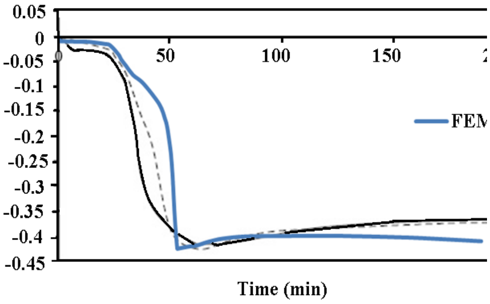


Figure 10. Comparison of laboratory results and numerical analysis of displacement diagrams over time [11]

3. RESULTS AND DISCUSSION

3.1. Stress Distribution in Curved Damper

After the analysis of curved damper models in ABAQUS software, the results are extractable numerically and graphically. Figure 5 shows the way of stress distribution during the thermal loading process. It is worth noting that the stress distribution is according to von Mises yielding criterion. As it can be observed in the figure, the yielding area gets bigger by increasing the displacement applied to the damper. It was specified by investigating the results that the area in the middle of the damper has reached yielding, which shows its bending performance due to the effective curved geometry of the damper. The maximum stress appeared in the center of the interior curve of the curved damper, which is consistent with the way of elastic stress distribution from the total axial force and bending moment stresses.

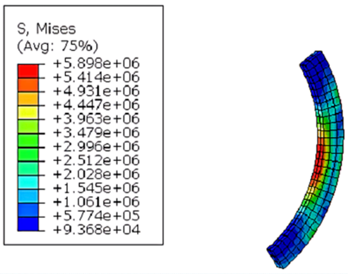


Figure 11. Stress distribution in curved damper during loading process [11]

3.2. Stress Distribution in Steel Connection

Stress distribution in the area of steel connection without damper and with curved damper is compared with each other in the figure. As it can be observed, after adding the curved metal damper to the steel frame, the stress in the connection of beam-to-column is reduced such that no segment of the lower flange of the beam reaches yielding. It was also specified that during the loading process, first the curved metal damper yields, and then by the increase of relative connection displacement, a small part of the upper flange of the beam was yielded in the area of connection to the column, which shows the effectiveness of the curved damper in improving the performance of steel connection. The level of the yielded area in the curved metal damper is also representing its high potential in absorbing and damping the incoming energy to the frame.

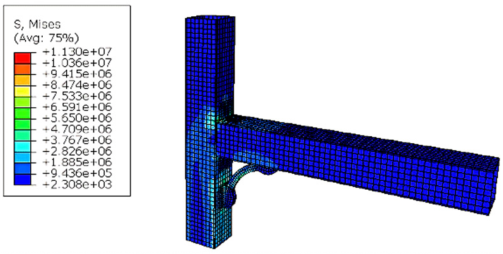


Figure 12. Stress distribution in the connection area of a steel structure with a curved damper [11]

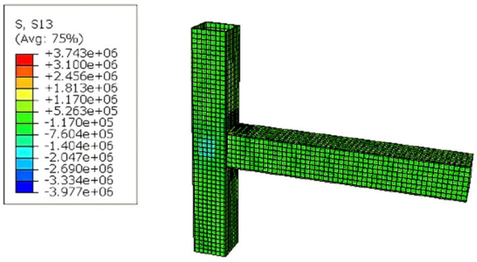


Figure 13. Shear pressure distribution in the joint area of a steel structure without a curved damper [11]

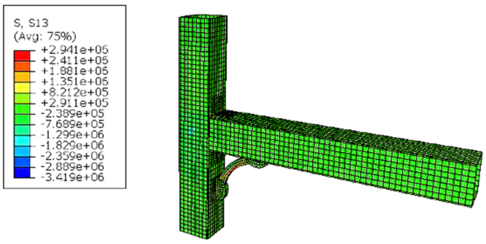


Figure 14. Stress distribution in the connection area of a steel structure with a curved damper [11]

3.3. Pressure Distribution in Steel Joints under Different Thermal Loads

The distribution of stress in the steel joint area equipped with a curved damper under the effect of different thermal loads in Figures 11 and 12 are compared. The curved current shows the effectiveness of the curved damper in improving the performance of the steel joint. The amount of area flowing in the curved metal damper also indicates its high capacity in absorbing and dissipating the input energy to the joint due to increased heat load.

The connection of a steel structure with a curved damper under the heat load of 765 °C provides 20.67% less displacement than a connection without a damper. Figure 18 shows the time displacement diagram of both types of connections without dampers and equipped with curved dampers. As the connection temperature of the steel structure with the curved damper increases from 765 °C to 1530 °C, the displacement of the connection increases from 35 cm to 44 cm. The dampers are under different heat effects.

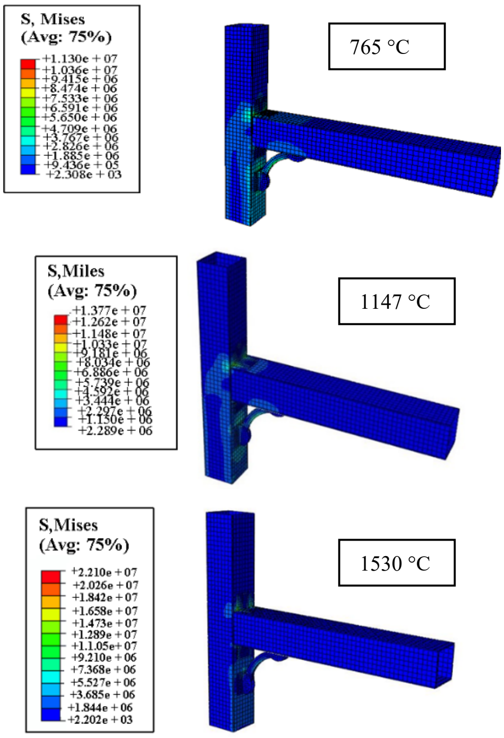
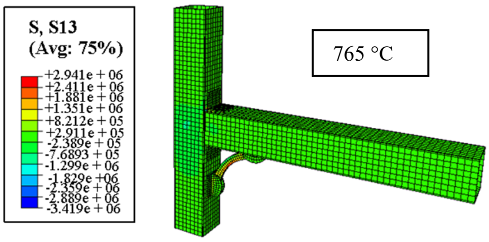


Figure 15. Comparison of stress distribution in the connection area of steel structure with curved shape damper under different thermal loads [11]



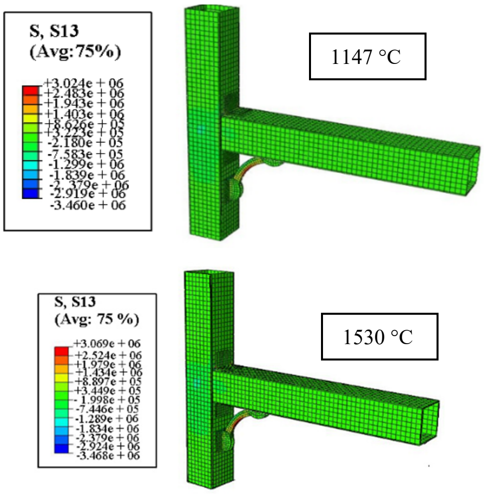


Figure 16. Comparison of shear stress distribution in the connection area of steel structure with curved shape damper under different heat loads [11]

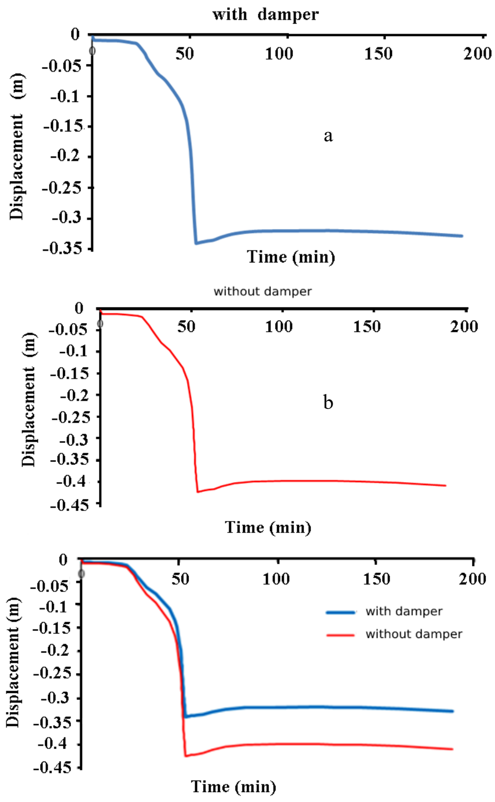
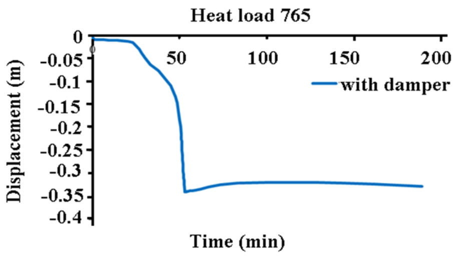
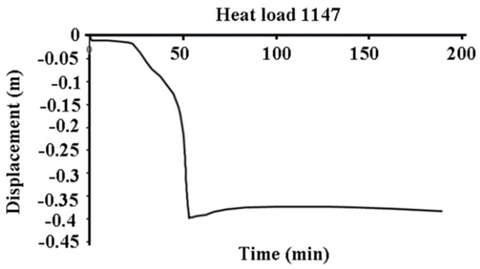


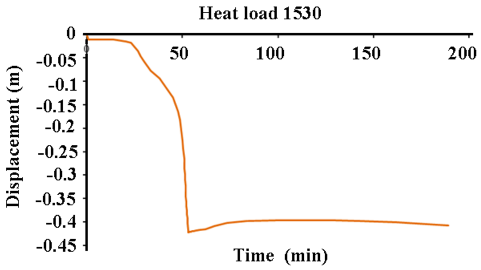
Figure 17. Comparison of displacement diagram of connection time with and without damper [11], a) Displacement of connection time with damper, b) Displacement of connection time without damper



Displacement diagram of damper connection time under the effect of heat load 1147



Displacement diagram of the connection time of the eggplant under the effect of heat load 765



Displacement diagram of the connection time of the eggplant under the effect of heat load 1530

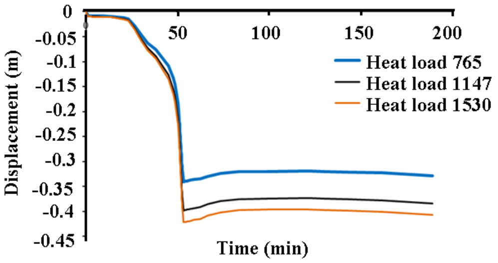


Figure 18. Displacement diagram of the connection time of the eggplant under the effect of different thermal loads [11]

By reducing the damper angle from 120° to 60° when the connection was subjected to a heat load of 765 °C, the energy loss increased and the maximum value was 60° (1854 KN.m) using the damper and the minimum was 30° (1770 KN) using the damper. m) was obtained. If you use a 30-degree damper, less energy loss occurs compared to a 60-degree damper (Figure 19).

By reducing the damper angle from 120° to 60° when the connection was subjected to a heat load of 1147 °C, the energy loss increased and the maximum value was 60° (2298.96 KN.m) and the minimum was 30° (2194.8). KN.m) was obtained. In fact, if you use a 30-degree damper, less energy loss occurs compared to a 60-degree damper (Figure 20).

By reducing the damper angle from 120° to 60° when the connection was subjected to a heat load of 1530 °C, the energy loss increased and the maximum value was 60° (3379.47 KN.m) using the damper and the minimum was 30° (3226.356 KN.m) In fact, if a 30-degree damper is used, less energy loss occurs at 4.52 compared to a 60-degree damper (Figure 21).

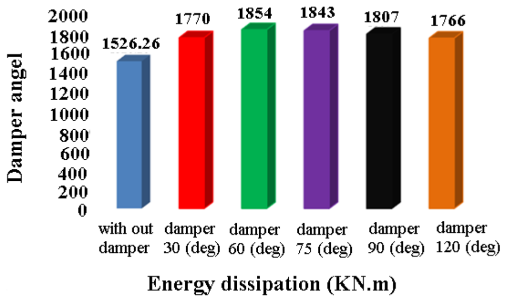


Figure 19. Comparison of the effect of curved damping angle on steel joint energy dissipation under heat load of 765 °C [11]

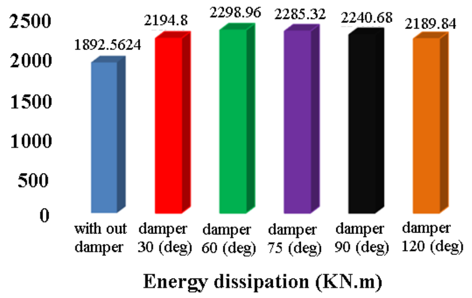


Figure 20. Comparison of the effect of curved damping angle on the energy dissipation of steel joint under heat load of 1147 °C [11]

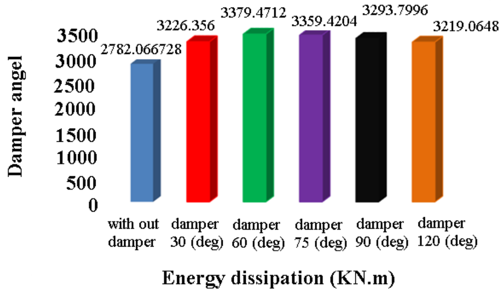


Figure 21. Comparison of the effect of curved shape damping angle on the energy dissipation of steel joint under heat load of 1530 °C [11]

4. SIGNIFICANCE OF STUDY

Since, in existing steel joints, the use of steel accessories can be considered as a reinforcement solution. As a result, the idea of using curved dampers in the improvement of steel joints is considered in this research. In addition, previous studies show that the behaviour of steel joints equipped with curved dampers against heat has not been studied so far. Therefore, the main innovation of this research is the feasibility study of the effect of curved shape dampers along with steel joints in improving performance against heat load.

5. RESEARCH METHODOLOGY

- Design of steel fittings.
- Modelling steel joints in ABAQUS software and performing nonlinear static analysis on them (steel joints without dampers) to perform validation.
- Add a curved damping system to steel joints and produce a new composite nonlinear model.
- Nonlinear static analysis of models with curved dampers again by ABAQUS software against load.
- Calculation of average nonlinear requirements of steel joints with and without curved shape damper obtained from nonlinear static analysis.
- Discussion on nonlinear force needs and displacement obtained from nonlinear static analysis.

The most important assumptions and limitations of the present study will be as follows:

➢ In order to evaluate the effectiveness of curved metal dampers in improving the performance of steel joints, in Abacus software environment, steel joints with rigid joints of one floor and one opening will be modelled.

➢ In the steel connection of the cross-section of the beam and column, a box type with the specifications of BOX300×10mm and an angle of L15×150×10mm will be used to connect the beam to the column.

➢ The studied models include a steel joint with rigid joints without dampers and a steel joint with rigid joints equipped with a curved metal damper. Both joints have an opening length and a height of 2000mm.

➢ Heat loads will include loads of 765-1147-1530 degrees Celsius.

➢ The angles used for the curved damper will be 30-60-75-90-120 degrees.

➢ The length of curved metal dampers is equal to 400 mm. Also, the depth of curved metal dampers will be equal to 80 mm.

➢ 30- and 60-mm thicknesses will be used for the curved damper thickness parameter.

➢ In modelling curved dampers, ST37 steel materials with a yield stress of 24 MPa and a final stress of 370 MPa were used. Also, the modulus of elasticity equal to 210 GPa and the Poisson coefficient equal to 0.3 was chosen.

➢ The connection of the beam and the column is clamped.

➢ The requirements of AISC360-16 will be used to design the steel connection.

6. CONCLUSIONS

In this paper, the effect of using curved metal dampers in improving the behavior of steel joints under the effect of heat load in Abaqus software was investigated. From all the issues raised, the following can be mentioned

- Examining the stress distribution in the curved metal damper, it was found that the maximum stress and the flowing area of the damper occur in its middle part, which indicates the effective geometry of the damper and its flexural performance. Also, a significant part of the curved damper has reached the delivery stage, which indicates the optimal use of the damper capacity in energy consumption.
- By increasing the length of the curved metal dampers, the values related to the initial hardness parameters, resistance, and energy dissipation capacity of the dampers decreased. So that the mentioned parameters decreased on average by about 31.45%, 24.2%, and 34.1%, respectively.
- As the depth and thickness of the curved metal dampers increased, their behavior improved and the values related

to the initial hardness parameters, strength and energy dissipation capacity of the dampers increased. The mentioned parameters increased on average about 50.4%, 61.47% and 31.25%, respectively.

- A steel joint with a curved metal damper performed better than a damper without a damper. Which shows the effectiveness of curved metal dampers in improving the response of steel joints.
- The distribution of stress in the steel joint area equipped with a curved damper under the effect of different thermal loads in the figure is compared. The curved current shows the effectiveness of the curved damper in improving the performance of the steel joint. The amount of area flowing in the curved metal damper also indicates its high capacity in absorbing and dissipating the input energy to the joint due to increased heat load.

NOMENCLATURES

1. Symbols / Parameters

$P\Delta$: Axial Load
Δ: Decentralization

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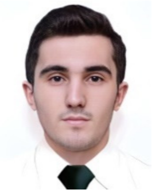

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