Analytical solution of the response of the I-shaped beam to the tubular column connections

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Abstract

Off-shore platforms constructed for oil and gas production are prone to high potential fire risks.These probable fire incidents may cause local or global structural damages, which in turn can result in serious consequences such as causalities, destruction of the facilities, and damage to the environment. It is therefore necessary to design these structures so as to ensure the least amount of loss after a possible fire event. Topsides of the offshore platforms are often provided with portal or truss-type structures. The truss, usually, consists of I-beams as chords and tubulars as diagonals. For the main joints of heavy topsides, I-beam-to-tubular leg connections with external diaphragms are usually employed. I-beam-to-tubular column connections with external diaphragms are important in decks and topside structures of the oil/gas platforms. In onshore steel structures, some experimental and numerical studies have been carried out to investigate the behavior of connections in fire. But, the number of studies on the behavior of connections of offshore platforms in fire and post-fire conditions are very limited. Previous studies on fire in offshore platforms mainly deal with the numerical simulation and risk assessment related to offshore structures exposed to fire. Recently, the authors have investigated the behavior of I-shaped beam to cylindrical hollow steel (CHS) column connections with external diaphragms, at elevated temperatures. In this paper a closed form analytical solution for the prediction of moment-rotation and the rotational stiffness-rotation curves of I-shaped beam to cylindrical column connections, commonly used in off-shore platforms, in room and elevated temperatures is presented. In order to define the behavior of the connection a bounding line moment-rotation model based on the works of Al-Bermani et al. was proposed. Observing the moment-rotation behavior of the connections using the numerical models, it was concluded that the bounding line model is suitable the model for determining M-φ and k_j-φ curves of these connections. The required yield and plastic moments in this model were provided by the authors extending Roark's relationships. Therefore, having the complete geometry of the connection and the yield stress value of the material it is easily feasible to determine the yield moment and plastic moment of the connection and its high temperature behavior. Then, having the values of yield and plastic moments it is possible to depict M - φ and k_j - φ curves of these connections in ordinary temperatures. Comparing the analytical results to experimental and numerical results indicates that the analytical relationships present acceptable approximations.The required yield and plastic moments in this model are provided as an extension to Roark's relationships. Relating the I-shaped beam to cylindrical column connection's stiffness in high temperatures to ordinary temperatures, it is then possible to extend the M - φ and k_j - φ curves of ordinary temperatures to high temperatures using the above equations. The results of this model are compared with those of a non-linear coupled mechanical-thermal finite element model previously provided by the authors, which was in turn validated using small-scale and large-scale experimental tests. Reasonable agreement has been found between the analytical model results and the experimental/numerical modeling results.

Keywords

I-shaped beam to cylindrical column, Off-shore platforms, High temperatures, Analytical model, Roark's relationships

1. Introduction:

connections are either fully rigid or fully pinned. The rigid connection assumption implies that the stiffness of the connection is significantly greater than that of the beam and column, while the pinned connection assumption indicates low stiffness of the connection compared to the connected members. The study by Nader and Astaneh[1], focusing on the behavior of connections, demonstrated that connections exhibit nonlinear behavior between complete rigidity and complete pinning; thus, connections in reality possess semi-rigid behavior. Recently, the impact of semi-rigid connections on the actual structural response has gained attention, and measures for analyzing structures with semi-rigid connections have been provided in several design codes for steel structures. The AISC code (Edition 360-22) specifically addresses semi-rigid connections and presents methods for their analysis and design. This edition includes sections dedicated to the nonlinear behavior of connections and their influence on structural performance [2]. In addition to the aforementioned codes, various studies have been conducted regarding the response of connections and their impact on structural behavior. Ali et al. analyzed the moment-rotation curves of I-shaped beam connections to tubular columns, showing that these curves can enhance the design of marine structures[3]. Pawar et al. also studied the nonlinear behavior of I-shaped beam connections to tubular columns in 2022, demonstrating that this behavior significantly varies under different loading conditions[4]. As noted, according to the review conducted by the authors of this article, a comprehensive analytical model for examining I-shaped beam connections to tubular columns has not yet been presented. Therefore, this research proposes a suitable model for predicting the behavior of I-shaped beam connections to tubular columns in offshore platforms at elevated temperatures.

2. Methodology

This article examines a comprehensive analytical method for predicting the moment-rotation and stiffness-rotation curves of I-shaped beam connections to tubular columns in offshore platforms at elevated temperatures. The yield moment and required plastic moment are derived from the developed Roark relationships[5]. In this context, the effective area and bending stress are initially calculated based on the design relationships for I-shaped beam connections to tubular columns. Subsequently, internal forces at various connection levels are computed using Roark's equations. Due to the similarity of the numerical $M-\varphi$ curves, a cantilever beam model is utilized to predict these curves, as well as the $k_j-\varphi$ relationship. Key parameters, including the yield moment (M_y), plastic moment (M_{pl}), rotation corresponding to the yield moment (φ_y), and rotation corresponding to the plastic moment (φ_{pl}), are calculated, with φ_y and φ_{pl} values proposed as 4.8 and 35 milliradians, respectively, based on numerical calculations. Figure 1 illustrates a typical connection of the I-shaped beam to the tubular column and the effective section in response to bending moment.

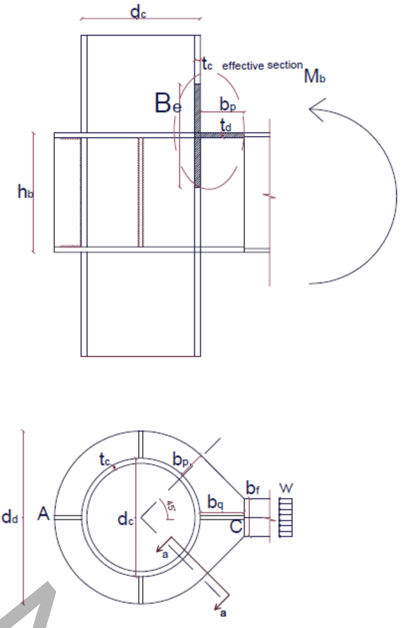

Fig1. A view of I-shaped beam to cylindrical column connection [5]

Additionally, the maximum von- Mises stress is expressed as a function of the connection geometry (α) and load (w) as follows:

$$\sigma_{von(\max)} = w.\alpha \tag{1}$$

The results obtained from this analytical model are compared with a nonlinear mechanical-thermal finite element model. For the numerical modeling of these connections, the ABAQUS 6.18 finite element software is employed, which has the capability to simultaneously analyze thermal and mechanical loads. In this analysis, the three-dimensional solid element C3D8T is utilized, allowing for the consideration of variations in stress and temperature.

3. Discussion and Conclusion

In this study, the prediction of moment-rotation curves for I-shaped beam connections to tubular columns at elevated temperatures has been investigated. To estimate these curves, yield moment, plastic moment, and elastic and plastic stiffnesses have been utilized. At high temperatures, these curves can be calculated using reduced values of elastic modulus and yield stress. New analytical relationships for calculating stiffness-rotation and moment-rotation of connections at high temperatures have been presented, which align well with the results of simulations. The results indicate that the accuracy of estimates at normal temperatures affects the accuracy of estimates at high temperatures, and the estimation error at high temperatures increases due to the accumulation of various errors. Overall, these relationships can serve as an effective tool for analyzing the behavior of connections under high thermal conditions. In Figure 2, the $\boldsymbol{M-\varphi}$ curve of the I-shaped beam connection to the tubular column of offshore oil platforms is presented, along with a comparison of analytical results and simulation curves for moment-rotation and stiffness-rotation for sample NS1 at a temperature of 650 degrees Celsius, using the analytical relationships provided in this paper.

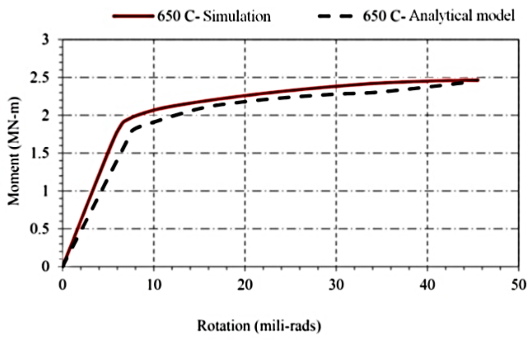

Figure 2: Comparison of moment- rotation curve of NS1 connection at 650^{oc} temperatures with bounded linear model and numerical model

4.Conclusion

This paper studied the behavior of I-shaped beam connections to tubular columns on offshore platforms under high-temperature bending moments. The computational approach in this research demonstrated that with complete knowledge of the connection geometry and the applied moment, the maximum stress in the effective section can be easily calculated using the derived relationships presented in this chapter. The continuation of the problem-solving process led to the extraction of relationships for determining the yield moment and plastic moment. Observing the moment-rotation behavior of the connection in numerical models revealed that the cantilever beam model is the best representation for explaining the $M-\varphi$ and $k_j-\varphi$ behaviors of these connections. With the yield moment and plastic moment established, along with assumed values for yield strain and plastic strain, the $M-\varphi$ and $k_j-\varphi$ curves for these connections were plotted. A comparison between the analytical model results for the $M-\varphi$ curves and the numerical model results showed a good agreement.Furthermore, by establishing a relationship between the stiffness of I-shaped beam connections to tubular columns at normal and elevated temperatures, the extracted relationships for determining the $k_j-\varphi$ and $M-\varphi$ curves at normal temperatures were extended to high temperatures. The analytical results obtained for the moment-rotation behavior of the connection at elevated temperatures were compared with the numerical model results, indicating that the analytical model can effectively predict the $M-\varphi$ and $k_j-\varphi$ behaviors of the connection at high temperatures.

It is worth noting that the results of this study and the extracted ductility parameters are applicable within the standard fire range (and not at other heat levels) and can be utilized for various standard fire temperatures. Additionally, a review of reputable articles regarding the ductility of these connections at high temperatures, particularly in recent years, revealed that there has not been extensive evaluation in this area.

5. Reference

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