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Full Length Research Paper

Finite element analysis of bolted column base connection without and with stiffeners

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Column base plates are analyzed and designed on the assumption that the plate is rigid and its thickness is determined from the cantilever action of the plate projection beyond the column face. In the case of column base plates with stiffeners, the plate thickness is determined by considering its bending and some parameters, which define the boundaries. In the present research two aspects are investigated, the adequacy of the present provisions on the design procedure of base plates with stiffeners and degree of rigidity of the connection with foundation. The three dimensional models are analyzed and compared with the known laboratory test results under axial load and axial load with moment. The results show good agreement between finite element analysis and experimental test.

Key words: Finite element analysis, steel connection, column base plate, rotational stiffness, rigidity.

INTRODUCTION

The design procedure of column base plates is based on the assumption that the base plate is rigid and consequently, the pressure distribution under the plate due to applied loads is linear. Besides, the plate thickness is determined by the cantilever action of the plate beyond the column face loaded by the pressure under the plate. By a common logic the thickness of a stiffened base plate is determined. The past researches show that pressure distribution is somewhat higher in region where the column directly sits down on the plate (Di Sarno et al., 2007; Targowski et al., 1993). This real situation will result in a lower plate deflections and moments and hence, the assumption of uniform pressure distribution becomes a conservative approach. Analytical studies to base plate behavior as compared with experimental investigations are limited. The basic reason for using approximate design procedure is that, although the pressure distribution under the base plate is localized, but there is not a solid procedure to figure out this variation (Krishnamurthy and Thambiratnam, 1990).

There are cases in which the column bases classified as hinges often posse fairly significant rotational stiffness and cases in the column bases classified as rigid may exhibit considerable deformation. In this research, the effects of stiffeners in the base plate behavior are investigated from two points of view; first, the extent to which the flexural stresses in base plate is reduced, in other words, the amount of base plate thickness reduction without violating the allowable stresses. Besides, the plate thickness can have a distinct effect on connection stiffness and moment capacity in case of more rigid connection.

Second, column bade plates deform particularly in rotation. This rotational behavior is usually idealized as pinned or fully rigid. But in most of the cases column bases show a high semi-rigid behavior, which influences significantly the global frame response.

The present work focuses on rotational characteristic of stiffened base plates when compared with the experimental results of unstiffened base plates which have been done by Jaspart and Vandegans (1998).

Structural model of the experimental unstiffened base plate is constructed and analytical investigation is carried out using finite element method. The results of the analysis are compared with the experimental ones. It is shown that adding stiffeners to column base plates altars rotational behavior towards a more rigid connection.

Stiffened base plates are used extensively both in hinged and rigid connection frames and so far adequate

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analytical and experimental researches have not been carried out on the subject. There is doubt about the present design provisions; it is not clear to what extent the thickness can be decreased without violating certain pre-specified stresses and how the thickness will affect the connection behavior.

There is question about the full rigidity of this type of column base plate, if it is assumed as a rigid connection in frames, the structural deflection and stability is determined not conservatively. In the present research, both the base plate thickness and its rigidity is taken under consideration. The stiffness of the connection is an important factor in accurately predicting structural deflection. No doubt the pin-ended assumption is conservative; nevertheless it is important to make accurate prediction of deflection which influences the structural stability.

In spite of vast use of column base plates and adequate examples on pin-ended and rigid-ended column base plates in most textbooks, there is not a solid procedure to determine the rigidity of the connection. Laboratory tests have shown that the main factors which govern column-base behavior are well known: (1) base plate thickness and size, (2) bolt size and bolt length confined in concrete (Del Coz Díaz et al., 2006; Hon and Melchers, 1988; Shi et al., 2008). It is clear that the behavior of column bases can be best described in terms of P-M-θ curves, where *P* is axial load, *M* is applied moment and θ is rotational deformation.

ANALYTICAL STUDIES OF COLUMN BASE PLATES

The three-dimensional domain modeled for the analysis of the column base plate consisted of the column stub, base plate, with or without stiffeners and anchor bolts. The concrete foundation support for the steel plate was assumed flexible by means of proper elements under the base plate. These elements are only capable of transmitting compression stresses to foundation. When separation of the plate from the support in a region takes place and nodes on the underside of the plate tends to pull away, the underside elements have no share in transmitting stresses. Inversely, proper elements has been chosen for anchor bolts so that by increasing moments they become active in transmitting only tension stresses. In the present analysis material non-linearity is taken under consideration. The accuracy of the analysis depends upon the foundation flexibility. To achieve this, the stiffness of elements underside of the plates is chosen based on the following relation at the beginning of the analysis (Laplume et al., 2000).

$$K = {(E_c A_c)}/{h} \quad (1)$$

Such that E_c is the young modulus of concrete, A_c is the mean area of concrete parallelepiped associated to a node of the base plate and h is the height of concrete foundation.

The connection shown in Figure 2 at first is designed based on the Iranian structural steel specifications (Irani, 1996) and then, finite element analysis of the model is carried out based on the relation 1. The outcome of the analysis was not satisfactory; no agreement is observed between the code specifications and the numerical analysis. Although, the code specifications are very conservative, nevertheless, flexural stresses computed from the finite analysis were much smaller than the code design stresses.

Since the main objective focuses on the behavior of stiffened column base plates when compared with unstiffened, the main criteria for selecting stiffness of elements underside of the plates was taken as the Iranian steel code specifications. That is, the element stiffness was chosen so that after numerical analysis, the base plate flexural stresses do not exceed the allowable limits of the code specifications.

In order to assure appropriate results from the three-dimensional models for the analysis of the column base plates, the following conditions have been made on the elements under the plate; (1) Sufficient number of these elements is chosen to increase the accuracy of the analysis; (2) these elements are capable of transmitting only compression forces, and have no stiffness in case of tension forces; (3) stiffness of these elements is known; (4) these elements are spread uniformly under the plate.

AXIAL FORCE ONLY

Part of the main research is based on comparative study of the generated stresses in the stiffened and unstiffened column bases under the applied loads. Furthermore, an attempt has been made to investigate the present design provisions of the stiffened column base plates, which are used extensively in Iran (Irani, 1996). As mentioned earlier, because of the complexity of the concrete behavior and non-linear pressure distribution under the base plate, design provisions on the allowable stresses of unstiffend column base plate is chosen as criteria for investigation of the stiffened base plates in the comparative study. Stiffness of elements under the base plate is chosen so that the maximum flexural stresses in the plate do not exceed the allowable ones. Then, the computed element stiffness is taken as a basis for the analysis of stiffened column base plates. Choosing stiffness of elements under the base plate based on the Equation 1 does not result in a proper result. As an example, for a non-standard column with 2IPE180 and normal length a column base plate with dimensions 450×450×31 mm based on the design provisions has been selected. The three dimensional analysis of the column base plate connection considering the stiffness of

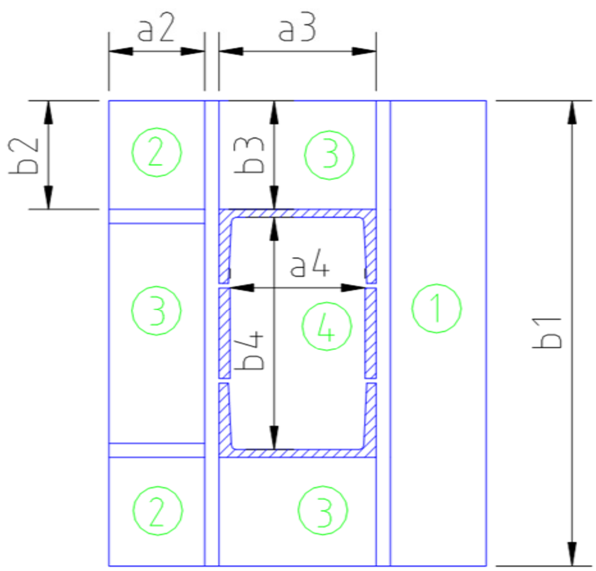

Figure 1. Different regions of a stiffened column base plate (Irani, 1996).

elements under the plate based on the Equation 1 has resulted in flexural stresses with a magnitude of $51Mpa$ which is highly unconservative.

In the present provisions on the design of stiffened column base plates, as it is shown in Figure1, plate is divided to different regions so that the behavior of each region is different. Plate is analyzed based on the assumption that it is rigid, the thickness of plate in region 1 is determined from the cantilever action of the plate projection beyond the column face. Behavior of region 2, which is restrained in two sides and free in the other two sides, is assumed as region 1 (Irani, 1996).

As it is demonstrated in this research, moment in this region is high and plate thickness design based on it will be very conservative. Besides, various numerical analyses have shown that the anchor bolt hole in this region does not have any effect on the overall plate behavior and its thickness. Region 3 is restrained from three sides and region 4 from four sides, various analysis of the modeled connection have shown that, plate thickness design based on the available provisions for these regions will result in proper results. Furthermore, adding stiffeners around four sides of the column base plate will increase its rigidity and the plate thickness can be reduced considerably when axial forces are present.

Finite element results

In the present of axial force only, for a non-standard column with 2IPE180 and design force of 610KN a column base plate with dimensions 450×450×31 mm based on the design provisions has been selected (Irani, 1996). As shown in Figure 2a, the plate is divided to 567 shell elements with 616 flexible elements under the plate. Successive analysis of the connection model and proper selection of the stiffness of elements under the plate,$1430\ N/mm$ the flexural stresses of $180.40Mpa$ in the plate is obtained. As shown in Figure 2b, a stiffened column base with 150 mm height and 10 mm thick stiffeners has been designed based on the design provisions and moments produced in region 2. The plate thickness is obtained as 30 mm, which is very thick. Finite element analysis of the model resulted in a maximum flexural stress of $76Mpa$ which shows design of plate thickness based on the moment obtained in region 2 is very conservative. Now, if this column base plate is designed based on the moment obtained in region 3, a 20 mm thickness is obtained and finite element analysis of the model reveals a maximum flexural stress of $149Mpa$ which by comparing to allowable stress of $144Mpa$ is acceptable. Adding stiffeners around the column base plate will increase its stiffness, as shown in Figure 2c, a 10 mm thick plate is added, the design provisions gives 16 mm column base plate thickness which is in good agreement with finite element analysis with flexural stress of $147Mpa$. The height of the peripheral plates is chosen as 30 mm in the finite element model. The analysis shows their effectiveness in improving column base plate stiffness. Table 1 shows some the finite element analysis of the column base plate models briefly.

AXIAL FORCE AND MOMENT

Various experimental laboratory tests have been performed on the base plate shown in Figure 3a (Jaspart and Vandegans, 1998). After modeling the connection, a number of non-linear analyses have been performed. The base plate with dimensions of 340×220×30 mm is modeled by 816 shell elements and 875 underside elements. To assure more precise results in the finite, element analysis a fine mesh is considered. The column stub section IPB160, which is used in the laboratory test, has been modeled as shown in Figure 3a. As in the test, the non-linear analysis has been accomplished for three different cases of axial force of 100, 400, 1000 KN and variable bending moment between zero and 100 KN.m. The analysis was performed so that moment-rotation curve resulted from the analysis coincides with the test results. This causes the unknown parameters, the stiffness of elements under the plate and anchor bolts are determined. Based on these known parameters another connection, a column base plate with stiffeners as shown in Figure 3b, is modeled. The stiffener thickness is chosen as 10 mm in the analysis, the detail is demonstrated in Figure 4a. Because of the complex behavior of concrete under the plate, it is impossible to

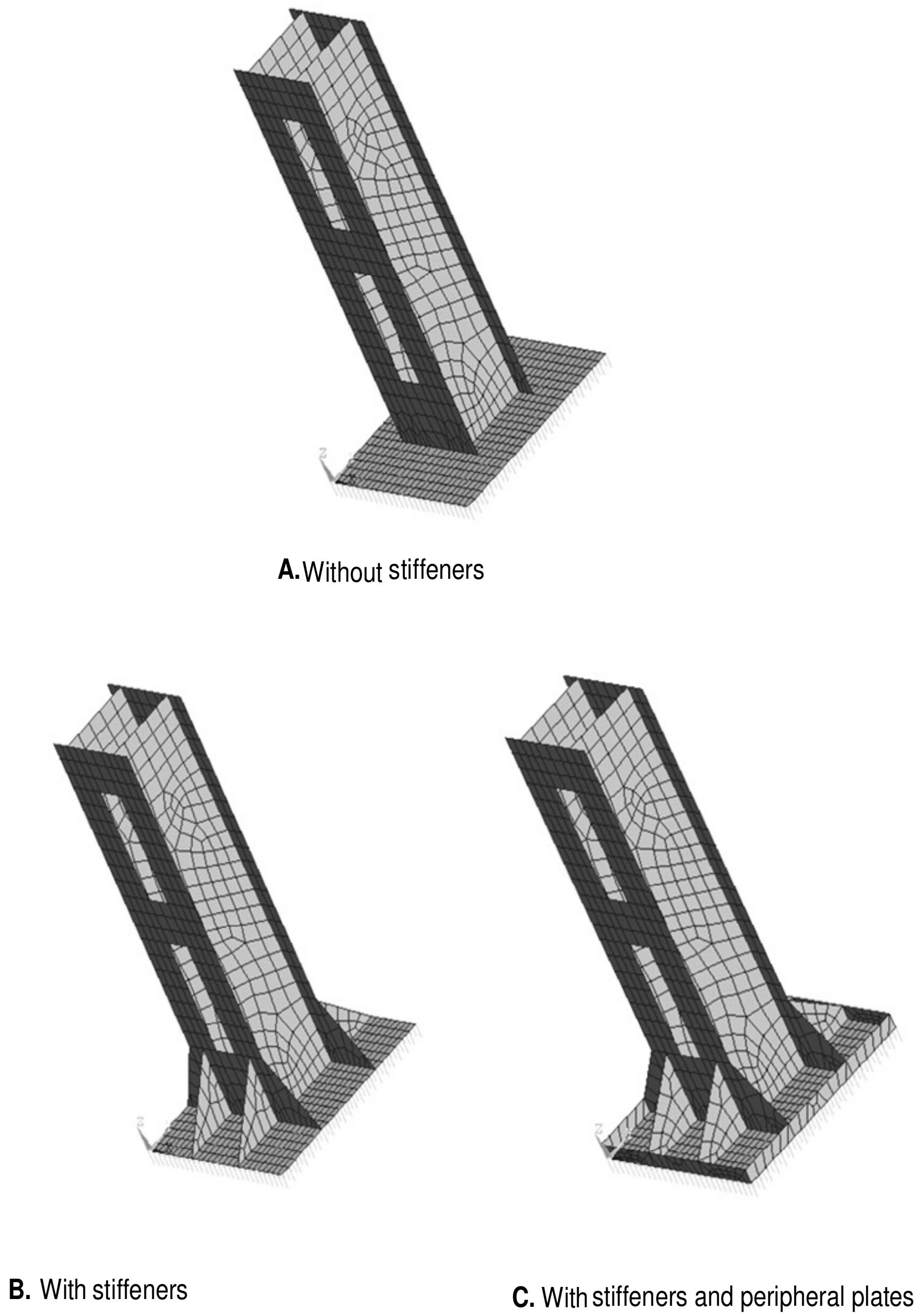

Figure 2. The three-dimensional models of the column base plate (axial force only).

Table 1. A brief on the finite element analysis of connection models (axial force only).

Plate thickness (mm)	Condition of base plate	Maximum flexural stresses in the analysis (Mpa)	Allowable flexural design stress (Mpa)
31	Without stiffener	180.40	180
30	With stiffeners	760	144
20	With stiffeners	149	144
16	Stiffeners+Peripheral plates	147	144

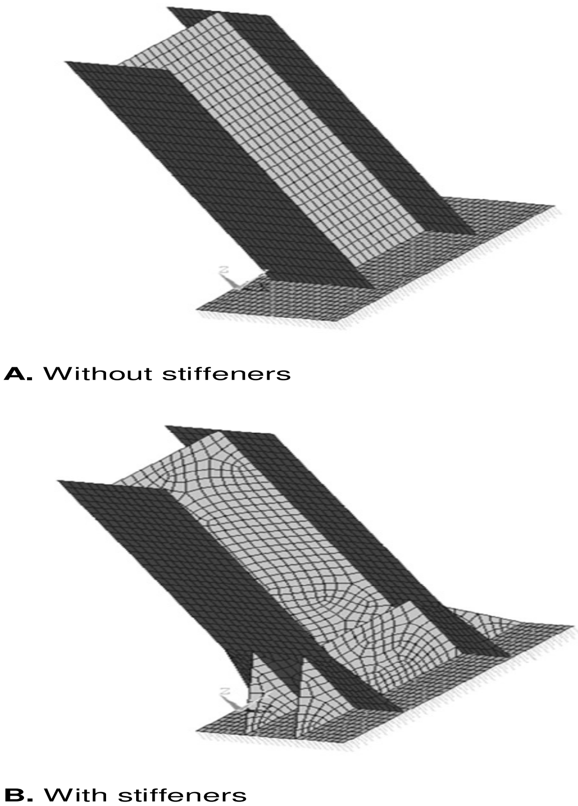

Figure 3. Analytical models of column base plate without and with stiffeners (axial force and moment).

determine the stiffness of these elements.

Thus, calibrating the model based on the test result seems inevitable. In cases when axial force is present, the stiffness, KN, of elements under the plate is unknown and in cases when both axial force and moment are present, the stiffness of anchor bolts is added to unknowns of the analysis. As mentioned earlier, the elements under the plate must transit only compression forces. When separation of the plate from the support in a region takes place and nodes on the underside of the plate tends to pull away, the underside elements have no share in transmitting stresses. Inversely, element chosen for anchor bolts become active in transmitting only tension stresses when moment is increased.

Effects of base plate stiffeners

The detail of the column base plate without stiffener, which is used in the laboratory test, is shown in Figure 4b. Adding stiffeners as shown in Figure 4a, modifies this column base plate. By comparison of the test results and the finite element analysis, the unknown stiffness of elements under the plate and anchor bolts is determined. Based on these known parameters, the effects of stiffeners on overall behavior of the connection are investigated.

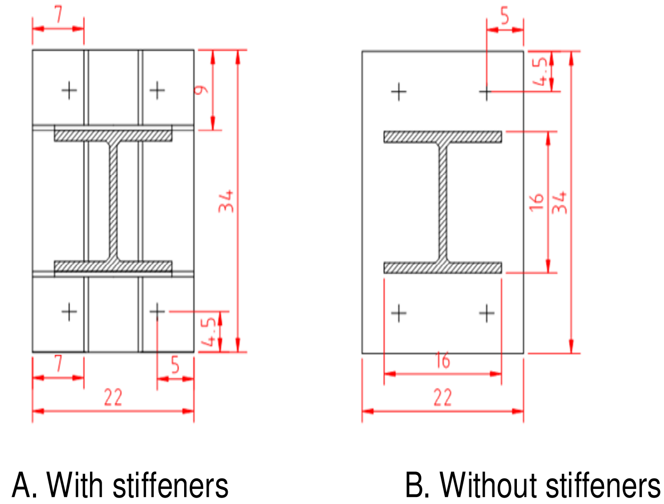

Figure 4. Column base plates used in the test and analysis.

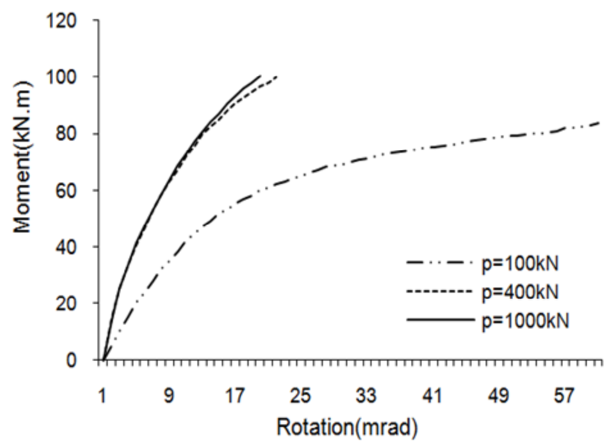

Figure 5. Moment-rotation curves resulted from the laboratory tests (Jaspart and Vandegans, 1998).

The results of the laboratory tests without stiffeners for different cases of axial force and varying moment in terms of moment-rotation curves is shown in Figure 5 (Jaspart and Vandegans, 1998). The results of finite element analysis of the stiffened column base plates are illustrated in Figures 6 to 8. As it is observed, by comparison of two different cases with and without stiffeners, the rigidity of the connection is increased. These adding stiffeners to column base plates altars rotational behavior towards a more rigid connection. Furthermore, increasing the axial force causes the connection to be more rigid. As in the case of 100, 400 and 1000 KN axial force, the connection rigidity is increased 15.4, 21.5 and 47.1%, respectively. No doubt, the connection rigidity is increased but the behavior does not reach completely to a rigid connection case.

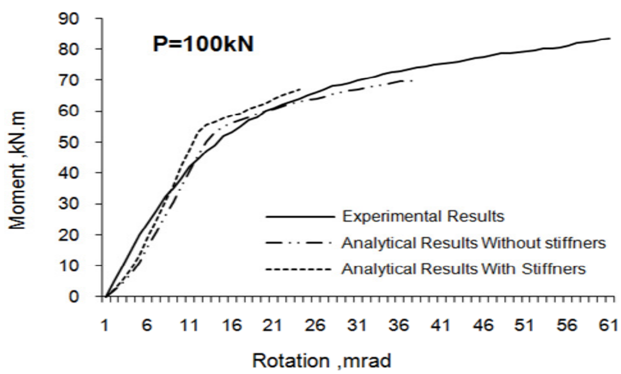

Figure 6. Comparison of the test results and numerical (Analysis for P=100 KN axial force).

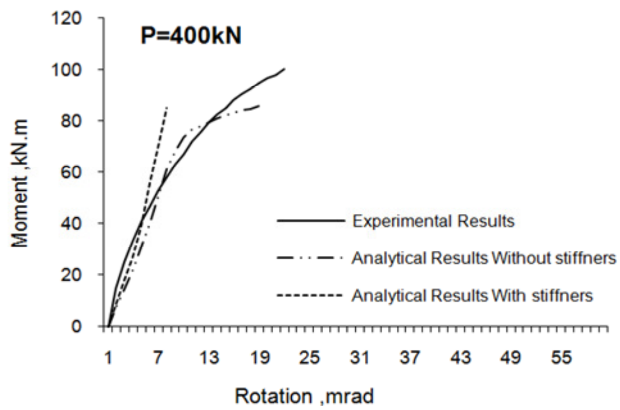

Figure 7. Comparison of the test results and numerical (Analysis for P=400 KN axial force).

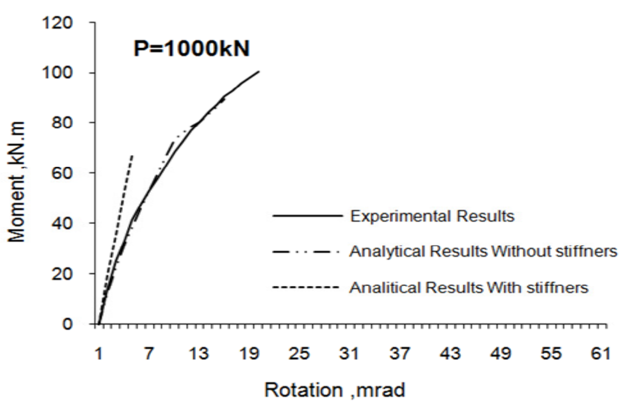

Figure 8. Comparison of the test results and numerical (Analysis for P=1000 KN axial force).

Other parameters such as plate thickness and anchor bolts diameter have a significant effect on the connection rigidity. As it shown in Figure 9, by increasing the plate thickness, the rigidity of the column base plate has been

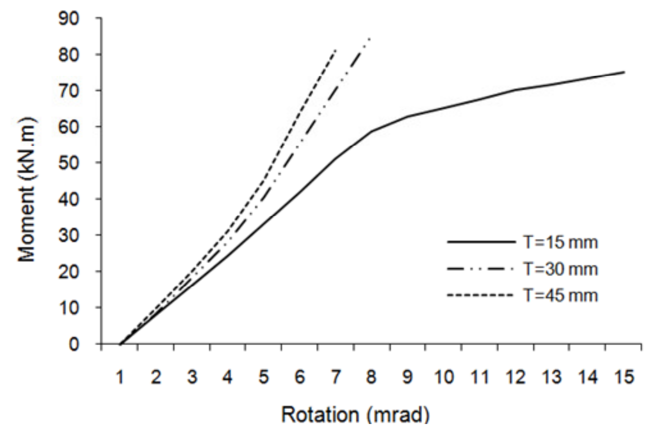

Figure 9. Effects of plate thickness on the connection rigidity.

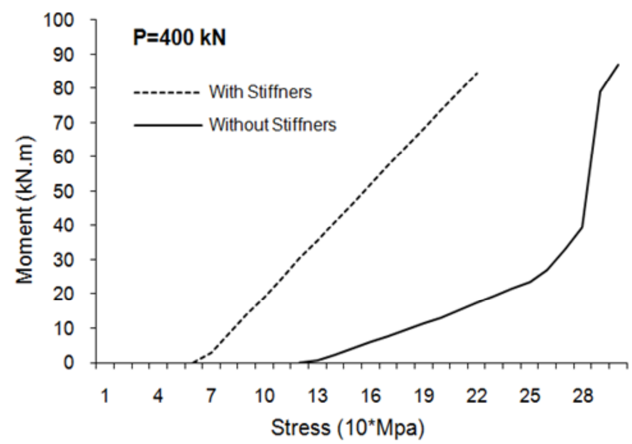

Figure 10. Noticeable effect of stiffeners on reducing flexural stresses.

improved. In order to illustrate how effective are stiffeners in reducing plate flexural stresses, one case has been shown in Figure 10.

CONCLUSIONS

In this research, the suitability of the present provisions on the design procedure of base plates with stiffeners and degree of rigidity of the connection with foundation has been investigated. Accuracy of finite element modeling was also performed by comparison with experimental results. Briefly, the results of this research can be stated as follows.

Present design provisions of stiffened column base plates are conservatives to the same extent as design of unstiffened column base plates. Care must be taken that design of stiffened column base plates based on the moments generated at corners, region 2, will result in a thick base plate which is very conservative. So this region should not be considered in the design process.

Column base plates demonstrate resistance against rotation to some extent even if they are designed or idealized as a fully pinned connection. Inversely, the column bases, which are classified as rigid, may exhibit considerable deformation. It has been demonstrated that, adding stiffeners will shift the connection behavior toward a more rigid situation but does not guarantee a fully rigid connection. However, other parameters such as increasing base plate thickness or anchor bolts diameter alters rotational behavior towards a more rigid connection.

Care must be taken when modeling frame supports as a rigid connection, since in reality achieving such a condition is in doubt and influences significantly the global frame response, the structural deflection and stability are not determined correctly.

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