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Contribution of the SidePlate Beam-Column Connections to the Seismic Responses of Special Moment Frames

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Abstract**—**The present study is an attempt to demonstrate the significant levels of contribution of the moment-resisting beam-column connections with side plates to the earthquake behavior of special steel moment frames. To this end, the moment-curvature relationships of a regular beam-column connection and its SidePlate counterpart were determined with the help of finite element analyses. The connection stiffness and deformability values from these finite element analyses were used in the linear time-history analyses of an example structural steel frame under three different seismic excitations. The top-story lateral drift, base shear, and overturning moment values in two orthogonal directions were obtained from these time-history analyses and compared to each other. The results revealed the improvements in the system response with the use of SidePlate connections. The paper ends with crucial recommendations for the plan and design of further studies on this very topic.

Keywords**—**Seismic detailing, special moment frame, steel structures, beam-column connection, earthquake-resistant design.

I. INTRODUCTION

THE earthquake resistant design of regular residential and commercial structures cannot fully rely on the elastic design philosophy. Resisting the most severe seismic excitations in the elastic range of response is a rather challenging task, since it necessitates the use of large member sizes, particularly for the vertical load-bearing members of the structure. This conservative design is atypical for structures with low degrees of significance due to the high construction costs. In this respect, regular structural systems are expected to dissipate a significant portion of the earthquake-induced free energy within the inelastic range of deformations. Structures susceptible to inelastic material response during the design earthquake need to be provided with sufficient deformation capacity at a particular lateral strength. The adequate deformability of a structure without compensating from its strength to a major level is also denoted as the ductility, which constitutes the leading aspect in the inelastic seismic design of structures.

Unlike lateral strength, providing a structure with sufficient ductility and deformation capacity is an exhausting task due to need for various major and minor details in the system. The ductile behavior of the entire structural frame strongly depends on the resistance and ductility of moment-resisting beam-column connections. The ductile behavior of the connection regions can only be achieved by surpassing the triaxial state of stress at the surface of contact between the column flange and the beam bottom flange. In this way, the shear stresses, which cater for the plastic deformation capacity of the connection region, can govern the beam-column connection behavior. The devastating effects of this triaxial state of stress were commonly observed in the 1994 Northridge earthquake. These undesired effects were exacerbated in the presence welded flange-bolted web (WFBW) traditional connections [1]. To overcome the brittle response of the connection regions, the ANSI/AISC 358-16 [2] standard presents the so-called prequalified beam-column connections with specific dimensions and details that can easily tolerate significant ground excitations.

The present study pertains to the efficiency of one of the prequalified types of connections in ANSI/AISC 358-16 [2], which is the SidePlate (SP) moment-resisting connection (Fig. 1). This type of connection offers the following advantages as compared to the conventional pre-Northridge WFBW connections:

1. The physical separation of the beam and column prevents the formation of a triaxial stress state at the connection. Many cases of failure in the Northridge earthquake were associated with the triaxial stress concentrations at the joint regions, which are unavoidable in the case of direct contact between the beam and column.
2. The side plates, which sandwich the column, avert the distortion of the panel zone by supporting the column web in resisting the unbalanced shear forces.
3. The extension of the side plates into the beam provides the plastic hinges to be more distant to the column face. In this way, the amount of dissipated energy increases without the need for the enlargement of the beam section.
4. The generality of the welds in this connection type are in parallel direction to the load, and therefore, the ductility of these welds is improved when compared to traditional connections, in which the flange welds are in perpendicular direction to internal forces.
5. Cover plates above and below the beam compensate for the differences between the beam and column widths.

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6. Solely using fillet welds in this type of connection prevents the involvement of any concern for the notch effects in the connection region.

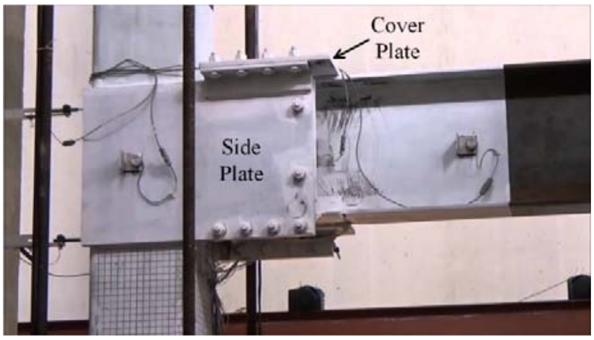


Fig. 1 SidePlate connection [3]

Significant effort has been put forward in the literature to unfold the effects of the SP connection type on the frame behavior. Engelhardt and Sabol [4] underscored the significance of beam cover plates in the joint regions to achieve ductile connection region behavior based on a total of 12 tests on full-scale specimens. Deylami and Ashraf [1] adopted the thickness values of the cover, side and shear plates as the analysis parameters and conducted detailed finite element analyses (FEA) on SP connections. These analyses indicated that SP connections have remarkable energy dissipation capacities and these capacities are not affected by the side plate thickness to a major extent. Chou et al. [5] used side plates to rehabilitate the existing beam-column connections. The tests on unrehabilitated and rehabilitated WFBW specimens depicted the efficiency of side plates to reduce the tensile strains in the bottom flange of the beam in the vicinity of column face. Shiravand and Deylami [6] investigated the applicability of the SidePlate connection details to I-beam to double-I built-up column steel connections. Nonlinear FEA on traditional connections, where the beam is directly welded to the cover plate, and the proposed SidePlate connections indicated that the SidePlate connections can be classified as full strength. The ductility of the connection was shown to exhibit a substantial increase with the use of this new connection type. Jalali et al. [7] conducted nonlinear seismic analyses on steel beams with different height and a side-plate connection subassembly. The connection region was modeled with an elastic panel zone and two degrading rotational springs that represent the critical connection section. Seismic demand hazard curves were established based on the application of the probabilistic seismic demand analysis approach to the analysis results. Nejad et al. [8] established the effectiveness of this connection type in allowing the connected beam to develop full catenary action and inelastic capacity in the case of a sudden column loss.

The studies on SidePlate connections in the last couple years concentrated on the applicability of this connection type to the concrete filled steel tubular (CFST) column-steel beam connections and the improvement to be achieved thanks to this connection detail. Within this scope, Huang et al. [9] tested full-scale walled column-H-beam specimens. The column flange and web dimensions in the panel zone and the extension of the side plates were adopted as test parameters. This study also presents theoretical bending capacity equations for three different failure modes of the connections with side plates, namely the plastic hinging of the beam away from the connection, failure of the weld between beam flange and side plate and the flexural failure of the side plate. Among the three tested specimens, the one with plastic hinging in the beam reached the highest ductility value due to the complete elastic behavior of the panel zone and plastic behavior at the desired location on the beam. In the search for effective connection details for CFST column-steel beam connections, Zhang et al. [10] designed and applied a side plate connection reinforced with an arc expanded cover plate (ACPSP connection) and a grooved side plate connection reinforced with a cover plate (GSPCP connection). This study mostly focused on the ability of the beam-column connections to withstand the catenary action in the case of the sudden loss of a column. These two new connection types improved the resistances of the beams to catenary action when compared to the traditional SidePlate connection. In a similar study, Liu et al. [11] examined the effectiveness of the SidePlate connection in wall-type CFST to I-beam connections. The pseudostatic cyclic loading tests and FEA indicated that the axial compression load on the column and the height of the side plates play an important role on the ductility of the connection region. Insufficient side plate height was found to trigger the failure of the gap between the beam and column, which in turn was responsible for the reduced strength of the connection. The tests of Liu et al. [12] on walled CFST column-steel beam joint specimens indicated that the flexural moments are resisted by the internal force couple along the flange of the side plate initially. Later, part of the bending moments is transmitted to the column web, while the remaining portion of these bending moments is resisted by the lower flange of the beam on opposite side of the connection region.

The detailed literature survey, summarized above, clearly indicates that the effects of the SidePlate beam-column connections on the frame seismic behavior have not been studied previously to a major extent. The present study pertains to the contribution of the SidePlate beam-column connection to the resistances of the structural steel frames to ground excitations and the changes in the seismic response parameters (top-story lateral drift, base shear force and base overturning moment) with the use of this prequalified joint type. In this respect, the moment-curvature relations of a traditional pre-Northridge connection and a SidePlate one were determined numerically using a commercial software [13]. Later, linear time-history analyses of a regular structural frame with the two different connection types were conducted under three different ground motion records. The analyses were realized with the help of another commercial matrix structural analysis software [14]. The comparison of the response parameters from the analyses on the two connection types helped the authors to clearly demonstrate the great contribution of the SidePlate connection to frame behavior.

II. ANALYSIS PROCEDURE

A. Connection Details

Two connections are adopted in the present study. The first connection is the SidePlate connection, whose dimensional details are illustrated in Fig. 2. The extension of side plates in this connection is connected to the beam cover plates with the help of bolts to increase the resistance of the connection regions to dynamic loading. The parts of side plates, sandwiching the column, are welded to the stiffeners of the column. In this way, the ductility of the connection regions increased since the fillet welds have the highest ductility if applied in parallel direction to the applied loading (lateral earthquake loading in this case). The column and beam have HEB500 and IPE450 cross-sections. The angles connecting the cover and side plates have L 110.25 cross-section. The grades of profiles, welds and M36 bolts of the connection are given in Table I.

The second connection is a regular haunched beam-column connection for special moment frames (SMF) and all dimensional details of this connection are illustrated in Fig. 3. The profile and bolt sizes and grades of this connection are identical to the first connection. In the second connection, the beam is welded to an auxiliary plate, which is bolted to the column. The stress concentrations in the connection region were also relieved with the help of a haunch. The welds, connecting the flanges to the auxiliary plate, are expected to have low ductility, due to the orthogonality of these welds to lateral loading.

B. Stiffness Analysis of the Connections

The moment-curvature relations of the two connections were determined with the help of analyses on subassemblage models, complying with the requirements of the section K2 of AISC 341-16 [15]. Accordingly, the connection models were composed of a single beam, attached to one side of the column, representing the edge and corner beam-column connections. As suggested by AISC 341-16 [15], the member lengths in the connection models were chosen based on the inflection points in the steel structural frame of the present study under earthquake loading. The inflection points on the beams are expected to develop at mid-length of the span in the case of lateral earthquake loading. Therefore, a beam length of 4000 mm was assigned to the models, considering the beam length in the analyzed frames was 8000 mm. Similarly, the upper and lower member lengths in the connection subassemblages had total lengths of 1000 mm and 1450 mm, respectively, based on the assumption that these inflection points develop at about 0.25 and 0.35 times the column length (4300 mm) from the center of the connection under earthquake loading.

The rotational stiffness analyses of both connections were conducted with the help of the IDEA StatiCa software [13] and the key parameters from these analyses are given in Table II. The structural analyses on the steel frame models adopted the values in this table for the connection region. The tabulated values clearly indicate that the SidePlate connection is superior to the haunched connection in terms of both strength and ductility for both reverse and forward directions of loading.

TABLE I
SECTIONS AND GRADES OF MEMBERS IN THE CONNECTIONS

Member	Section or Size	Grade
Beam	IPE 450	S275JR
Column	HEB 500	S275JR
Angles	L110.110.25	S355JR
Bolts	M36	10.9
Stiffener Plates	20 mm thick	S355JR
Side and Cover Plates	25 mm thick	S355JR
Fillet Welds	throat thickness in the range of 4.0-10.6 mm	E70xx[1]

[a] a specified minimum tensile strength of 70 ksi (482 MPa)

TABLE II
RESULTS OF THE STIFFNESS ANALYSES

Loading Direction	Parameter	Haunched	SidePlate	% Increase
Reverse	Bending Resistance (kN.m)	541.2	585.1	8.1
	Initial rotational stiffness[1](MNm/rad)	470.6	636.5	35.2
	Rotational Capacity (mrad)	24.8	25.8	4.0
	Class	Rigid	Rigid	-
Forward	Bending Resistance (kN.m)	541.2	585.1	8.1
	Initial rotational stiffness[1](MNm/rad)	1072.2	574.1	46.4
	Rotational Capacity (mrad)	24.2	25.9	7.0
	Class	Rigid	Rigid	-

[a] limit stiffness for the rigid joint 177.1 MNm/rad and pinned joint 17.7 MNm/rad

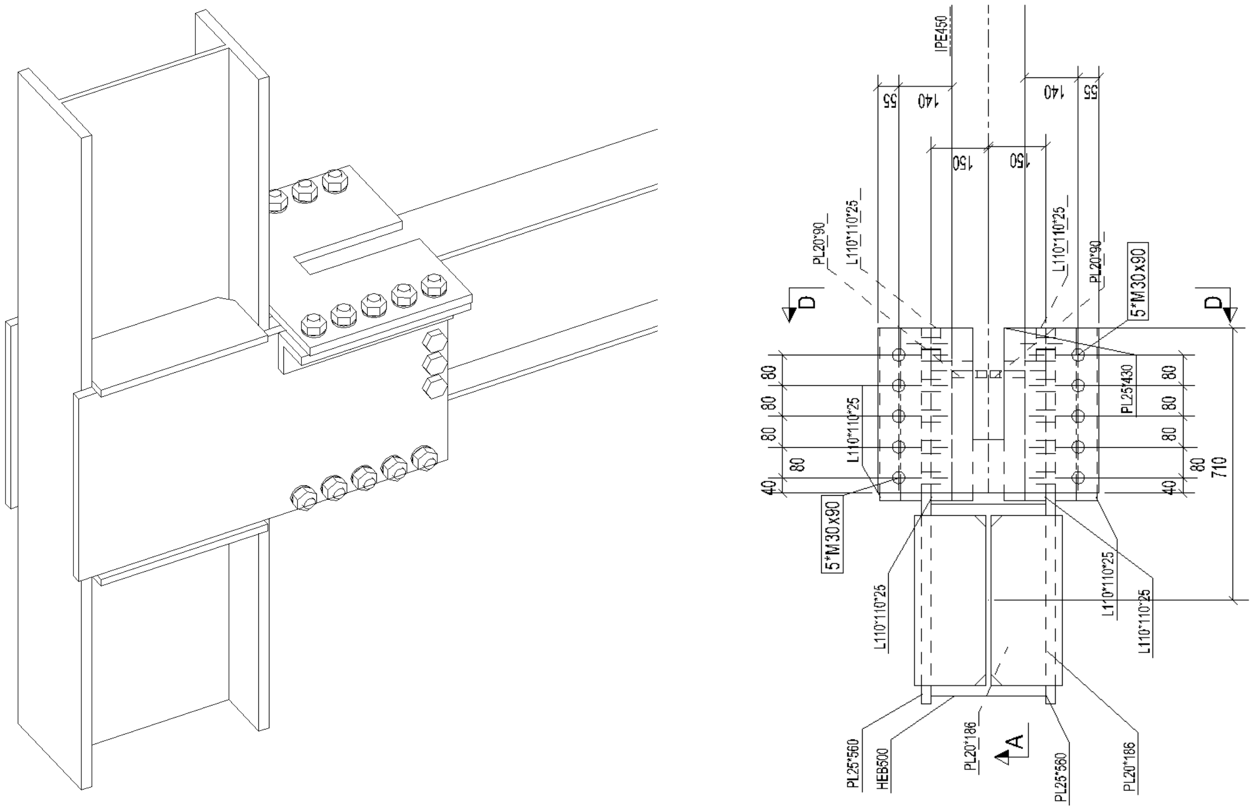
Only the rotational stiffness of the haunched connection in forward direction exceeds the respective value of the SidePlate one due to the contribution of haunch in this direction. One should remember that the ductility constitutes the most crucial parameter for the inelastic response of steel structural frames during an earthquake. The deformation capacities of the SidePlate connection were obtained to be 4% and 7% above the respective values of the haunched connection in the reverse and forward directions of loading, respectively.

C. Structural Model

A four-bay four-story steel structural frame (Fig. 4) was modeled in the SAP2000 matrix structural analysis software [14]. This benchmark frame was regular in plan and had no structural irregularities whatsoever. In this way, the contribution of this new connection detail to the seismic responses of regular structures was aimed to be unfolded. All columns were fixed to the ground. All beams and columns had cross-sections of HEB500 and IPE450 of grade S275JR.

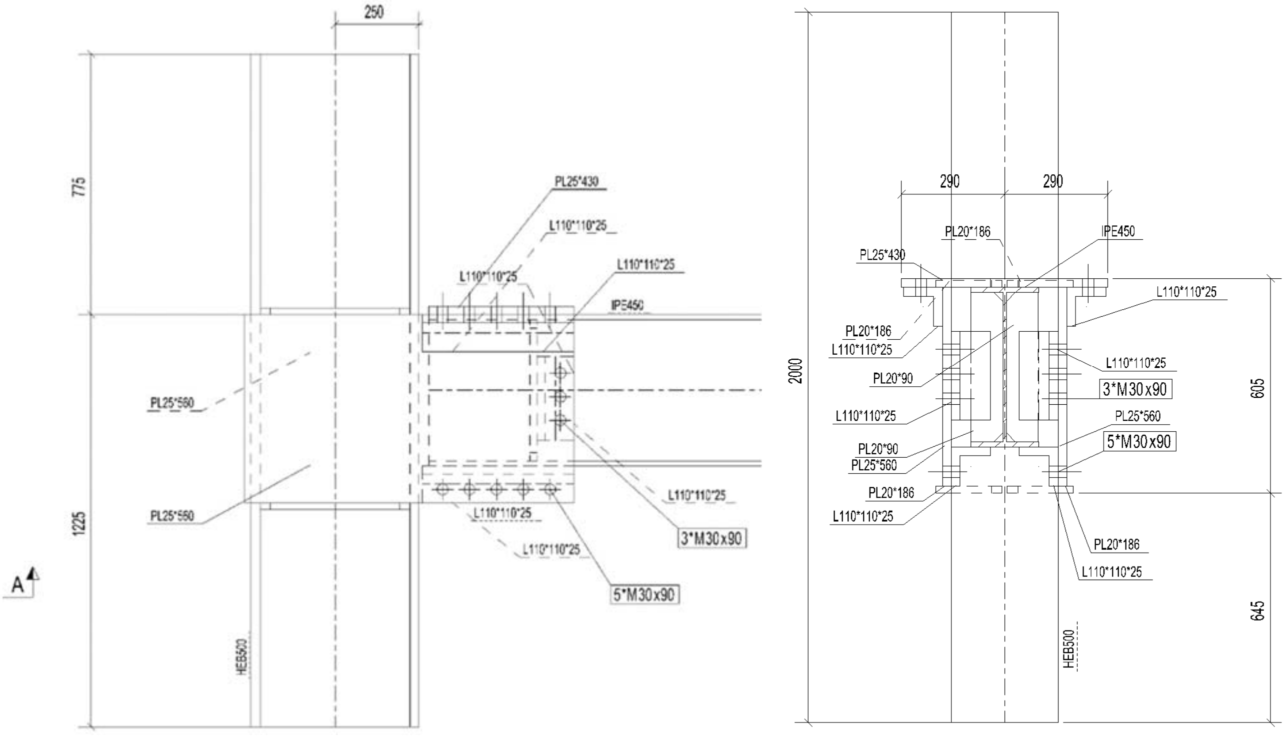
D. Earthquake Analyses

Linear time-history analysis method was used in the present study to examine the improvement in the overall earthquake performance of the benchmark structure with the use of SidePlate connection. Time-history analysis is the most realistic earthquake analysis method since it utilizes real ground motion records, scaled to the design response spectrum of the related structure. Furthermore, ground excitations, modified according to the local ground conditions of the location, can also be utilized in this method to obtain more realistic and reliable estimates [16].



(a) Isometric View

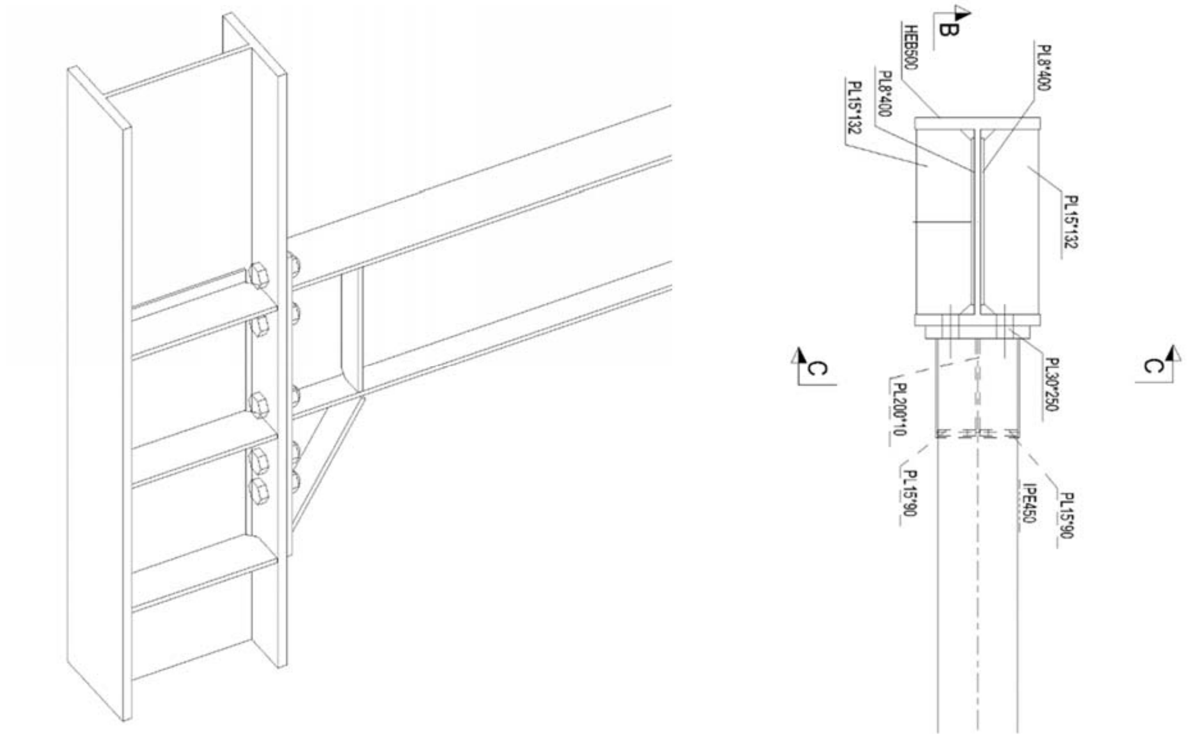
(b) Top View



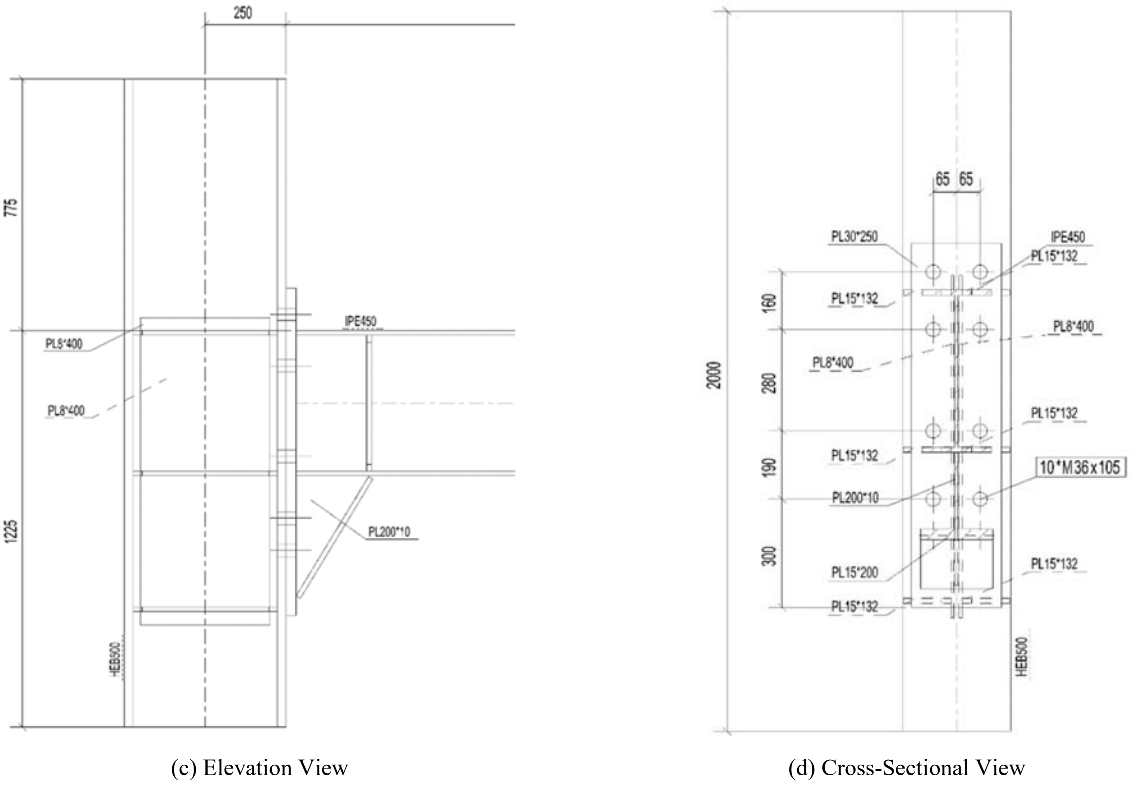
(c) Elevation View

(d) Cross-Sectional View

Fig. 2 SidePlate connection details



(a) Isometric View (b) Top View



(c) Elevation View (d) Cross-Sectional View

Fig. 3 Conventional haunched beam-column connection details

The American [17], European [18], Turkish [19] and Australian-New Zealand [20] practices allow the use of three ground motion records in the analyses as long as the maximum values of the structural response parameters (story drift, base shear, base overturning moment and story twist) are taken into account in the evaluation and comparison of analysis results. All these codes of practice [17]-[20] necessitate the simultaneous application of two horizontal and one vertical components of the earthquake record and choosing the records according to the seismic characteristics (peak ground acceleration, distance to fault and source mechanism of the seismic action) of the region. Based on the previous studies [21], [22], three records from the PEER website [23], namely the Bolu, Imperial Valley and Kocaeli records, were used in the present analyses. These records imitate the worst earthquake scenario of the City of Kirikkale, where the model structure was assumed to be constructed. The ground characteristics of the region were completely ignored in the present analyses by assuming full fixity at foundation level.

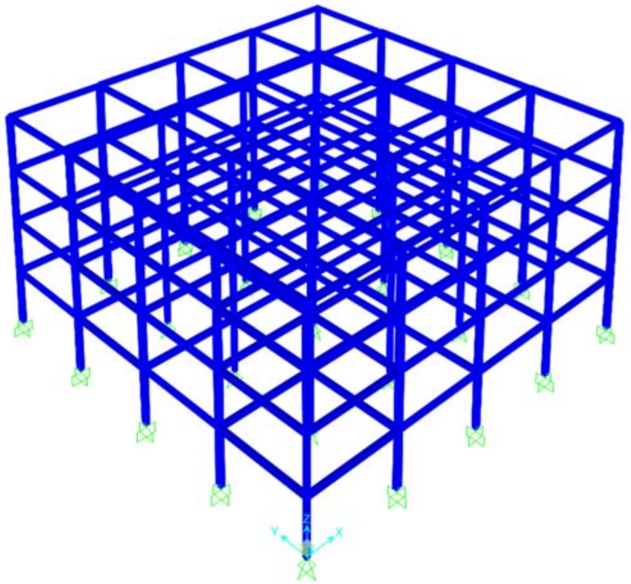


Fig. 4 Modeled structural frame

III. DISCUSSION OF RESULTS

Table III illustrates the structural response parameters for the two structural models in the case of three different ground motions.

The values in Table III indicate that the use of SidePlate connection in replacement for the haunched connection yielded to a general trend of increase up to 4.2% in the base shear and up to 3.5% in the base overturning moment. This replacement resulted in the reduction of the top-story lateral drift in some analyses, while increasing the drift in the remaining analyses. In general, the effect of improving the connection region on the story drift is much less than its effects on base shear and overturning moment. The increase in the lateral forces and bending moments for almost fixed values of lateral drift stems from the larger stiffness of the SidePlate connection as compared to the haunched connection. As the connections become more rigid, the general stiffness and strength of a structure increase. Similar lateral deflections result in greater internal forces and moments in the more rigid structural members, which in turn increase the forces and moments at the base of structure.

The almost unchanged values of the top-story lateral deflections, on the other hand, originate from the limited increase in the rotational stiffness of the connection with the use of side plates. The main superiority of the SidePlate connection is the tolerance to greater deflections in the inelastic range rather than its stiffness and strength. Hence, nonlinear time-history analyses on the same model structures will definitely demonstrate much greater differences between the seismic response parameters of these two models with different connection details. The linear analyses of the present study could only show the partial advantage of this connection.

TABLE III
RESULTS OF STRUCTURAL ANALYSES

Ground Motion	Dir.	Response Parameter	Haunc.	Side Plate	% Change
Imperial Valley	+ *x*	Base Shear (kN)	1729.6	1754.4	+1.4
		Overturning Moment (kN.m)	31986.6	31785.6	-0.7
		Lateral Drift (mm)	161.8	161.9	+0.1
	- *x*	Base Shear (kN)	1969.5	1978.2	+0.4
		Overturning Moment (kN.m)	50488.9	50856.0	+0.7
		Lateral Drift (mm)	196.3	194.9	-0.7
	+ *y*	Base Shear (kN)	1964.9	2017.4	+2.7
		Overturning Moment (kN.m)	50620.4	51022.2	+0.8
		Lateral Drift (mm)	195.2	199.0	+1.9
	- *y*	Base Shear (kN)	2469.4	2471.8	+0.1
		Overturning Moment (kN.m)	32944.3	32944.4	0
		Lateral Drift (mm)	204.8	203.5	-0.6
Bolu	+ *x*	Base Shear (kN)	1650.3	1661.5	+0.7
		Overturning Moment (kN.m)	49613.1	49605.2	-0.1
		Lateral Drift (mm)	203.2	201.9	-0.6
	- *x*	Base Shear (kN)	1943.5	1960.4	+0.9
		Overturning Moment (kN.m)	54848.4	55121.1	+0.5
		Lateral Drift (mm)	172.9	172.3	-0.3
	+ *y*	Base Shear (kN)	1950.5	1977.6	+1.4
		Overturning Moment (kN.m)	56906.8	56967.7	+0.1
		Lateral Drift (mm)	141.0	143.9	+2.1
	- *y*	Base Shear (kN)	1934.2	1966.4	+1.7
		Overturning Moment (kN.m)	50070.9	50278.1	+0.4
		Lateral Drift (mm)	164.2	166.7	+2.0
Kocaeli	+ *x*	Base Shear (kN)	1738.2	1736.4	-0.1
		Overturning Moment (kN.m)	36740.0	36834.2	+0.3
		Lateral Drift (mm)	190.0	190.1	-0.1
	- *x*	Base Shear (kN)	1529.4	1553.0	+1.5
		Overturning Moment (kN.m)	38419.0	38420.6	0
		Lateral Drift (mm)	190.4	190.2	-0.1
	+ *y*	Base Shear (kN)	1830.1	1906.9	+4.2
		Overturning Moment (kN.m)	40169.3	41603.4	+3.5
		Lateral Drift (mm)	228.3	234.2	+2.5
	- *y*	Base Shear (kN)	2312.7	2326.4	+0.6
		Overturning Moment (kN.m)	41195.9	40675.4	-1.3
		Lateral Drift (mm)	223.2	229.6	+2.7

IV. CONCLUSION

The present study is an attempt to unfold the advantages of the use of SidePlate connections in Special Moment Frames under seismic actions over conventional beam-column connections. For this purpose, two connections, including a conventional haunched one and a side-plated one, were designed. The moment-curvature relationships of the two connections were determined. Later, two structural models with no structural irregularities were developed for each connection

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type. Linear time-history analyses were conducted on both models by using three different ground motion records. These records were chosen based on the seismic features of the assumed location of the model structures. The two horizontal and one vertical components of each ground motion were applied to the structure simultaneously. The effect of the improved connection regions on the structural response was evaluated through the use of three response parameters, namely the top-story lateral drift, the base shear and the base overturning moment in both orthogonal plan dimensions.

The analyses indicated that the base shear and overturning moment values increased to a considerable extent, while the drift remained almost unchanged between the two models. The increases in the shear and moment values with the use of SidePlate connection were attributed to the increase in the structural stiffness thanks to the improved rotational stiffness of the connections. The linear analyses could not fully grasp the effects of the SidePlate connections on structural deflections. With the use of the full moment-curvature plots of the connection regions, the nonlinear analyses are expected to show that the structures with SidePlate connections undergo smaller lateral deflections thanks to additional reserve stiffness in the inelastic portion of the moment-curvature plot.

V. FUTURE STUDIES

The present study is the first stage of an analytical program. In this stage, only regular structural systems were analyzed and linear time-history analyses were conducted to identify the seismic performances of these regular frames. In the further stages of the study, frames with different structural irregularities (regular in plan, weak story, etc.) will be analyzed. What is more, nonlinear time-history analyses will be conducted to reach the damage states of the frames and their nonlinear deformations to uncover the actual performances.

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