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Ductile Moment Resisting Connections by Means of Drilled Cover Plates

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Abstract: Seismic behavior of a typical steel moment resisting connection is investigated and the influence of the connection behavior on the global frame performance is studied. It is proposed to shift the stress concentration from the connection face trough the cover plates by means of drilled holes. This will eliminate the unfavorable cracking mode and enhances the overall connection behavior. Based on finite element results, while the weld roots are released from stress concentrations, the sensibility of the weld root quality is diminished and the global structural performance and reliability is significantly improved.

Key words: Steel frames, moment connections, finite element analysis, earthquake resisting structures

INTRODUCTION

The local behavior of the beam to column connections has direct effect on the global seismic performance of the moment resisting frames. Insufficient stiffness, moment capacity or ductility capacity of the connections may cause uncontrolled deflection, local damage or total collapse of the structural system.

Primarily, significant stress concentration exists at the connection face. This stress concentration may result in premature failure of the connection elements and hence limit the connection seismic potential (Elnashai and Elghazouli, 1994). In welded connections the premature failure commonly happens in form of the weld root fracture caused by poor structural detailing or unsatisfactory weld root quality (Calado and Lams, 1998; Clifton *et al*., 2000). These regions are usually subjected to increased seismic forces. On the other hand, the usual constructive imperfections of the weld root and the intrinsic brittle behavior of the heat affected zone modifies the potential of the crack initiation and propagation through the material. These two form a suitable recipe for premature connection failure in form of brittle fracture.

It is proposed that one of the most efficient solutions to improve such connection shall be the reduction of the stress concentration at the weld roots. This might be done by means of reduced section of the beam or the connector elements.

Reduced beam section, is proposed by others to create such weak point at the beam element, which seems to be effective (Astaneh and Nader, 1991). Although they modify the ductility level of the connection significantly, they usually suffer from increased stress concentration at the beam web and significant decreased moment capacity. In addition the reduced section in this case usually consists of beam flange which is not easily replaceable after it is damaged.

Others proposed reduced sections for connectors, which seems more efficient. This way the web participation in nonlinear deformations is omitted. A predefined damage mechanism shall be expected in connectors which can be easily replaced after a strong earthquake.

Many researchers have proposed cast connections with variable flange thickness to create the required weak point (Fleischman *et al*., 2007). It seems effective, but it requires a very expensive casting process which is also very time consuming (Chang and Wu, 2007). The use of channel or angle connectors welded to beam and column flanges is also proposed by other researchers (Kumar and Rao, 2006). It seems effective, if the architectural limitations allow such geometry at the top and bottom level of the beam. The researchers propose reduced cover plate connection type to reach the required performance and reliability level. The schematic view of the original connection type is shown in Fig. 1. The reduced section is created by means of drilled holes at the cover plates. The proposed model shall be seen in Fig. 2. Considering the proposed terminology the weld roots are evidently released from stress concentrations. The major nonlinear mechanism takes place adjacent to the drilled holes. Reaching the whole expected moment capacity and

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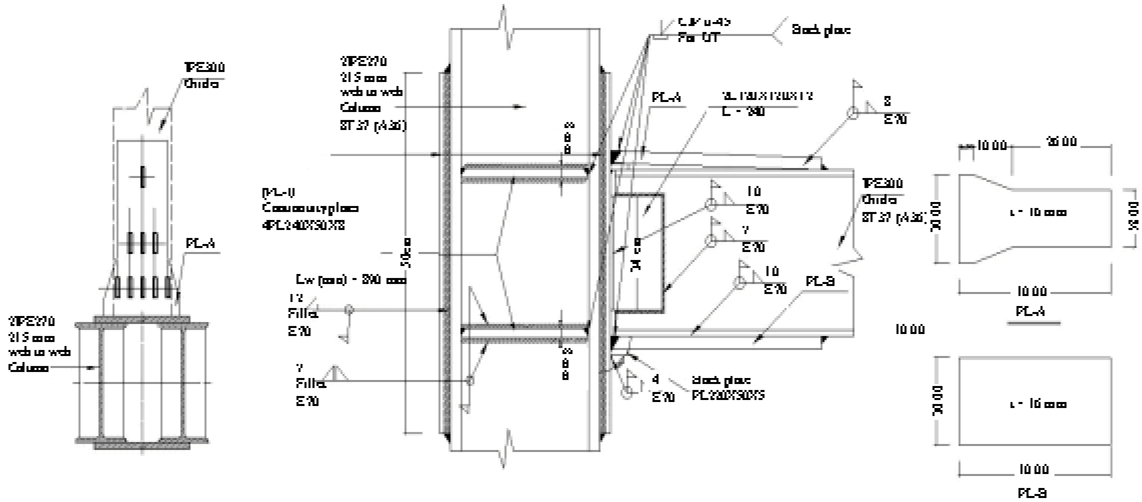

Fig. 1: The original connection detail

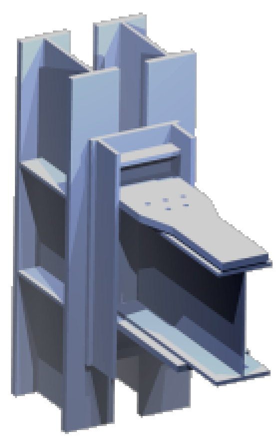

Fig. 2: 3D view of the proposed connection

sufficient rotational stiffness, the connection performs an excellent rotational ductility that might improve the overall structural deformation potential. In order to evaluate the connection behavior and to investigate the related parameters, nonlinear analyses has been performed on the finite element models of the connection and the hysteretic behavior is revealed. Joint elements, featuring the connection moment rotation relations are then assigned to finite element frame models to evaluate the global nonlinear behavior. This way the effect of the local connection behavior on the global performance is investigated by means of nonlinear static analyses.

SEISMIC EVALUATION OF MOMENT RESISTING CONNECTIONS ASSISTING COVER PLATES

Basically in such connections, the moment in girders are transferred to the columns in the form of a force couple from beam flanges to the cover plates and then to the full penetration welds. This is exactly the region with the amplified potential for the brittle fracture. The basic concept is to shift the stress concentration to somewhere inside the cover plate. Many parameters may contribute to the nonlinear connection behavior. The most important parameters are found to be as the following:

- The thickness of cover plates
- The thickness of the end plate
- Number and diameter of drilled holes
- Quality of the weld roots and the welding procedure
- Other previously studied parameters e.g., presence of continuity plates, detail of the shear connection, beam depth effect, panel zone relative shear capacity, the geometry of cover plates, the efficiency of fillet welds etc

From the above parameters the quality of the weld roots is evidently the most sensitive parameter in the unmodified connection type. Imperfections and possible inclusions in the weld material drastically affect the connection behavior usually forming premature brittle fractures. The weld inclusions cannot be directly modeled in finite element environments with ordinary methods in its random nature and the discrete geometry. Also they are hardly avoidable or very costly to eliminate in real construction. So the modifications are targeted to omit the weld quality sensibility. Further discussion about the weld quality effect is avoided. Valuable researches have been done on the issues mentioned in item (e). It is considered that the favorable conditions are satisfied so that the possible effect of such parameters shall be ignored.

Table 1: General specification of the finite element models

Finite element model label	End plate thick (mm)	Cover plate thick (mm)	Continuity plates (mm)	No. of drilled holes	Diameter of drilled holes (mm)	Finite element model label	End plate thick (mm)	Cover plate thick (mm)	Continuity plates (mm)	No. of drilled holes	Diameter of drilled holes (mm)
CVPL8	15	8	10	NA		CVPL10	15	10	10	NA	
CVPL12	15	12	10	NA		CVPL14	15	14	10	NA	
CVPL16	15	16	10	NA	NA	CVPL18	15	18	10	NA	NA
CVPL20	15	20	10	NA	NA	CVPL22	15	22	10	NA	NA
CVPL24	15	24	10	NA	NA	CVPL26	15	26	10	NA	NA
CVPL28	15	28	10	NA	NA	CVPL30	15	30	10	NA	NA
CVPL32	15	32	10	NA	NA	CVPL34	15	34	10	NA	NA
CVPL36	15	36	10	NA	NA	ENPL8	8	15	10	NA	NA
ENPL10	10	15	10	NA	NA	ENPL12	12	15	10	NA	NA
ENPL14	14	15	10	NA	NA	ENPL16	16	15	10	NA	NA
ENPL18	18	15	10	NA	NA	ENPL20	20	15	10	NA	NA
ENPL22	22	15	10	NA	NA	ENPL24	24	15	10	NA	NA
ENPL26	26	15	10	NA	NA	ENPL28	28	15	10	NA	NA
ENPL30	30	15	10	NA	NA	ENPL32	32	15	10	NA	NA
ENPL34	34	15	10	NA	NA	ENPL36	36	15	10	NA	NA
NOHOLE	15	15	10	NA	NA	1FI-6	15	15	10	1	6
1FI-8	15	15	10	1	8	1FI-10	15	15	10	1	10
1FI-15	15	15	10	1	15	1FI-20	15	15	10	1	20
1FI-30	15	15	10	1	30	2FI-6	15	15	10	2	6
2FI-8	15	15	10	2	8	2FI-10	15	15	10	2	10
2FI-15	15	15	10	2	15	2FI-25	15	15	10	2	25
3FI-6	15	15	10	3	6	3FI-8	15	15	10	3	8
3FI-10	15	15	10	3	10	3FI-15	15	15	10	3	15
4FI-6	15	15	10	4	6	4FI-8	15	15	10	4	8
4FI-10	15	15	10	4	10	5FI-6	15	15	10	5	6
5FI-8	15	15	10	5	8	5FI-10	15	15	10	5	10
6FI-8	15	15	10	6	8	6FI-10	15	15	10	6	10
7FI-8	15	15	10	7	8	7FI-10	15	15	10	7	10
8FI-6	15	15	10	8	6	8FI-10	15	15	10	8	10
9FI-6	15	15	10	9	6						

The other three parameters are discussed in the following. In order to investigate the interested parameters, finite element models of the connections are generated using the FINNL3D finite element code. The finite element model labels and specifications shall be seen in Table 1.

The FINNL3D finite element code typically facilitates hierarchical solid and shell elements enjoying a non-associated flow rule to predict the nonlinear behavior. A Multi linear sub-volume material model is also assisted to approximate the nonlinear plastic strain vector.

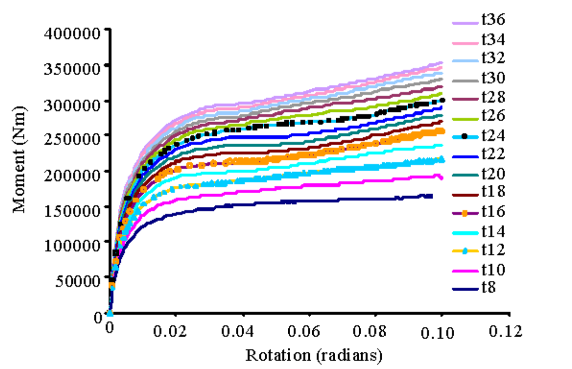

Fig. 3: The effect of cover plate thickness on the connection nonlinear behavior

THE EFFECT OF THE COVER PLATE THICKNESS

The cover plate thickness has direct affect on stiffness, yield moment and the ultimate moment capacity. Evidently the incremental effect is limited by the ideal beam stiffness and the moment potential. The nonlinear behavior of the connection with different cover plate thicknesses shall be seen in Fig. 3. The effect of the cover plate thickness shall be estimated for different occasions using normalized curves provided in Fig. 4-6. As it shall be seen in Fig. 5 and 6 when the relative thickness is increased about 2.00 the polynomial relations of the stiffness and the yield moment capacity seems to be horizontal, while the ultimate moment capacity curve seems inclined (Fig. 4).

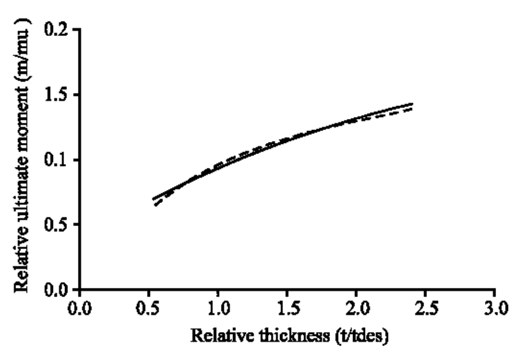

Fig. 4: The effect of the cover plate relative thickness on the relative ultimate moment capacity

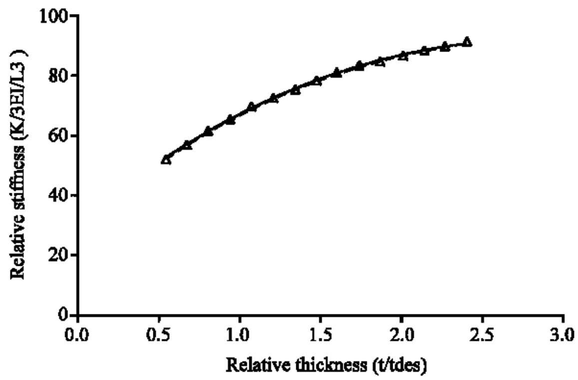

Fig. 5: The effect of the cover plate relative thickness on the relative stiffness

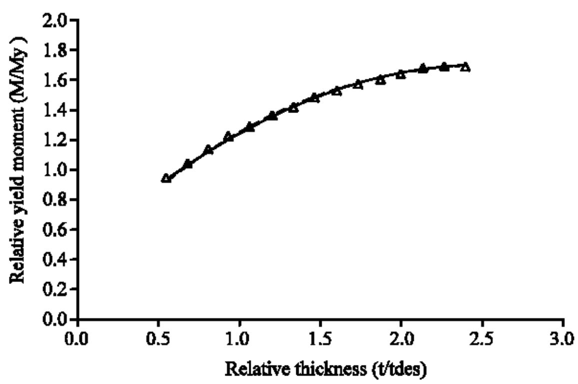

Fig. 6: The effect of the cover plate relative thickness on the relative yield moment

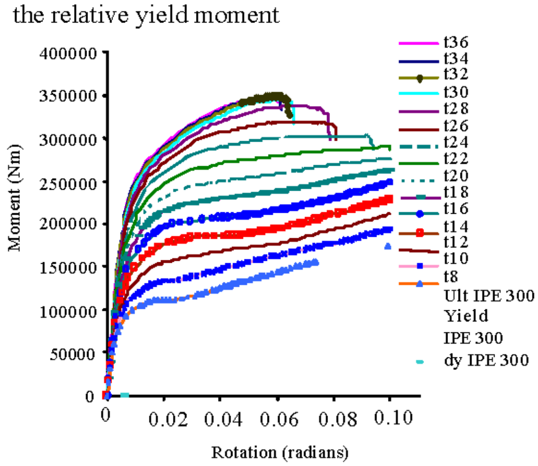

Fig. 7: The effect of the end plate thickness on the nonlinear behavior of the connection

THE EFFECT OF THE END PLATE THICKNESS

As it was predicted, the thickness of the end plate has a brilliant effect on the connection stiffness (Fig. 8)

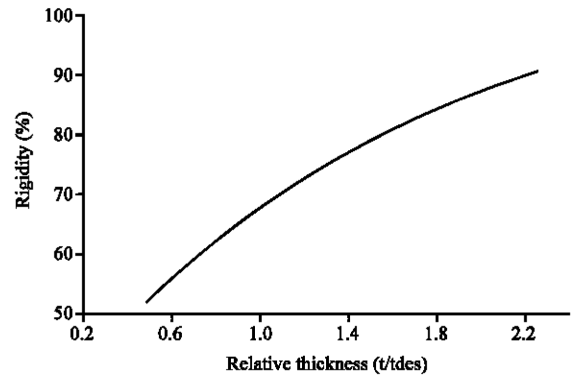

Fig. 8: The effect of the end plate relative thickness on the relative stiffness

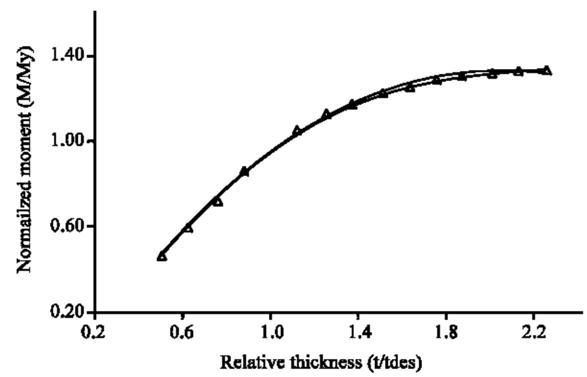

Fig. 9: The effect of the end plate relative thickness on the relative yield moment

while it has limited effect on the yield and the ultimate moment capacity. According to Fig. 9 and 10 it shall be noted that from the relative thickness above 1.70 the end plate has a constant effect on the connection moment capacity and the cover plate thickness shall control the connection behavior. The nonlinear behavior of the connection with different end plate thicknesses shall be seen in Fig. 7.

THE EFFECT OF DRILLED HOLES

While the drilled holes are disturbing the semi-steady stress flow in the cover plates, the different hole configurations might affect the nonlinear behavior, which is to be investigated.

To this aim, finite element models were created with different number and diameter of holes variant from one to nine holes and the diameter of 6 to 30 mm placed in a single line perpendicular to the beam longitudinal axis. The nonlinear behavior of the models shall be seen in

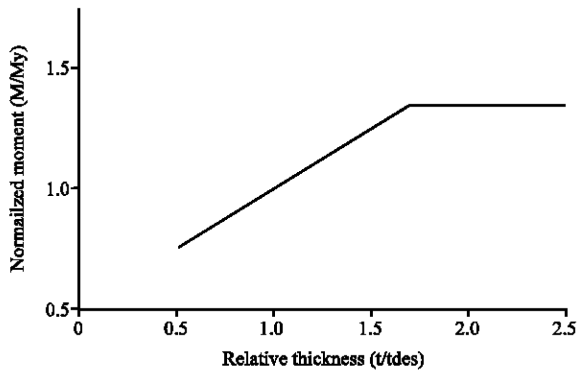

Fig. 10: The effect of the end plate relative thickness on the relative ultimate moment capacity

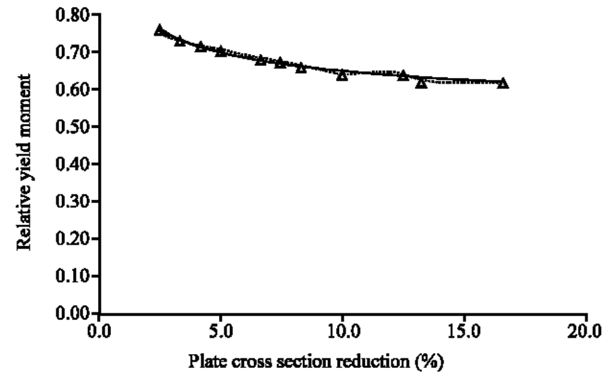

Fig. 13: The effect holes on the relative yield moment capacity

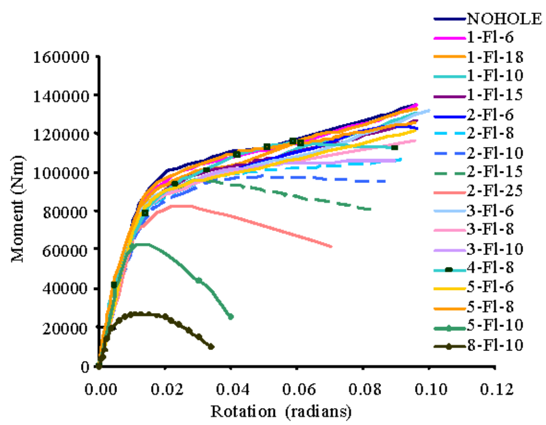

Fig. 11: The effect of holes on the connection behavior

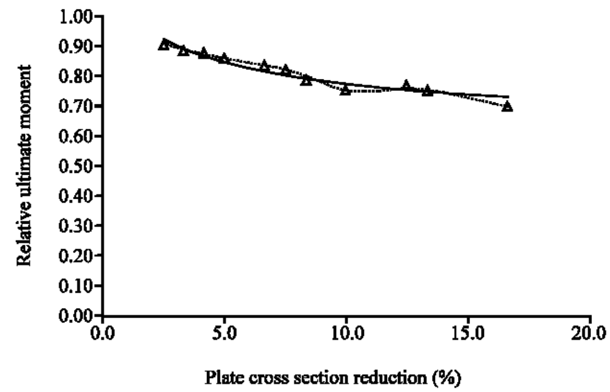

Fig. 14: The effect of holes on the relative ultimate moment capacity

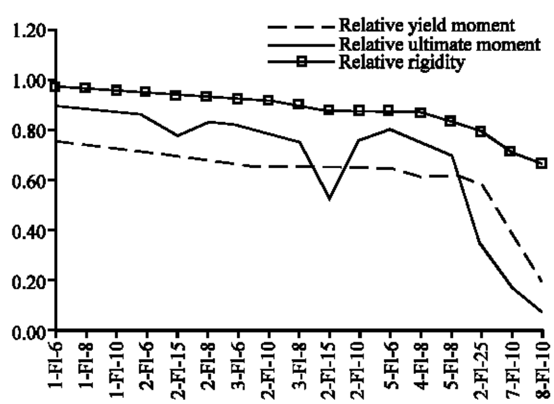

Fig. 12: Relative stiffness and moment capacity models

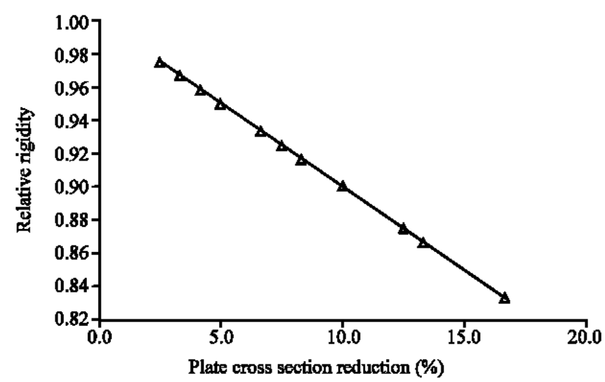

Fig. 15: The effect of holes on the relative stiffness

Fig. 11. As it was expected, feasible boundary shall be defined with medium number and diameter of holes. This way the connection behavior shall be optimized. Big holes provide boosted stress concentrations that reduce the connection capacity in form of premature yielding at the hole edge vicinity. Similarly large number of holes form thin plate strips between them, which are subjected to premature yielding of the cover plate, which is not beneficial. As it is evident from Fig. 10, when the hole diameter exceeds 1.25 times the plate thickness the connection ultimate capacity is starting to diminish significantly. In a similar way when the clear distance

between the hole boundaries is less than 0.80 times the plate thickness the ultimate moment capacity is significantly limited. Between these two extremes a stable performance shall be expected regardless of number and diameter of the holes and a suitable regression may be considered. After omitting the unfavorable configurations mentioned above, the effect of the area reduction of the cover plates on the relative yield and ultimate moment capacity and stiffness of the connection was investigated, which may be observed in Fig. 13-15, respectively. The unmodified connection model subjected to nonlinear deformations is shown in Fig. 16. The stress contours at the top and bottom cover plates are shown in Fig. 17 and 18, respectively. As it is evident the main stress concentration persists at the connection edge, specifically weld roots.

This is the main phenomena resulting in brittle fracture of the connection. The stress contours in cover plates are provided for the SPC3 and SPC4 in Fig. 19 to 22. As it is evident the stress concentration is completely shifted through the cover plates. Releasing the weld roots, a dominant yield mechanism is viable to happen. This phenomenon was approved by the experimental test performed on the mentioned specimens.

EFFECT OF CONNECTION BEHAVIOR ON THE GLOBAL PERFORMANCE OF MOMENT RESISTING FRAMES

To investigate the connection effect on the global frame performance, 12 frame models were generated. Frame models commonly have 6 spans of 5 m and one to

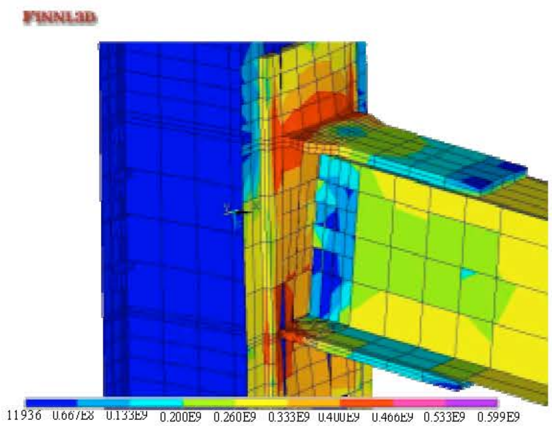

Fig. 16: SPC2 finite element simulation at the final rotation capacity

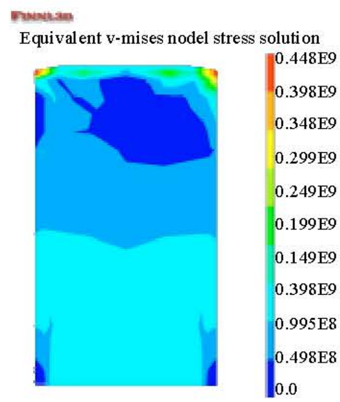

Fig. 18: c cover plate with no holes

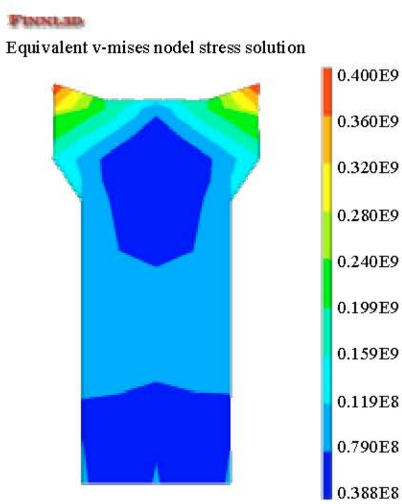

Fig. 17: Top cover plate with no holes

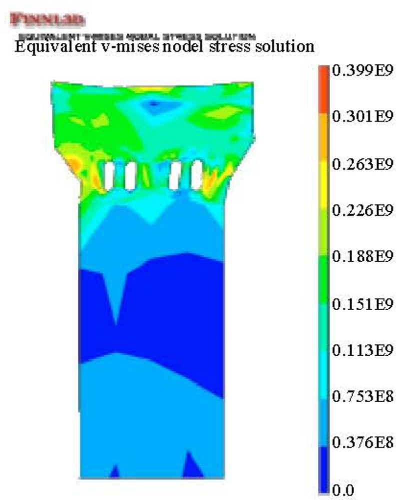

Fig. 19: Top cover plate SPC2

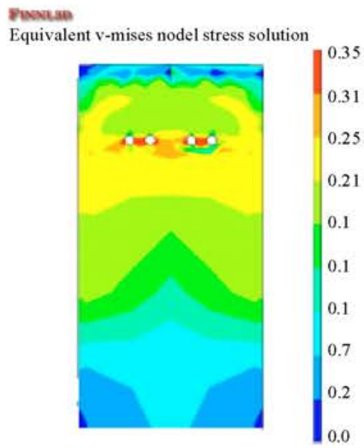

Fig. 20: Bottom cover plate SPC2

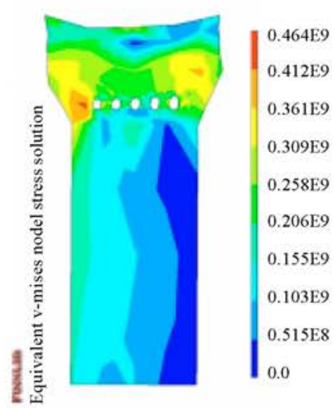

Fig. 21: Top cover plate SPC3

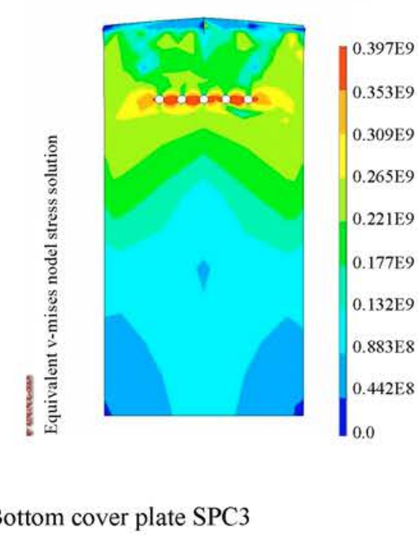

Fig. 22: Bottom cover plate SPC3

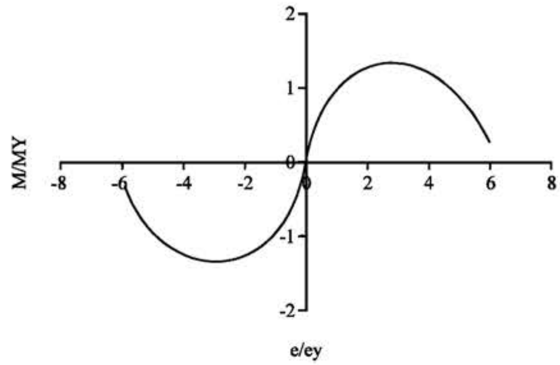

Fig. 23: Moment rotation curve of the unmodified connection

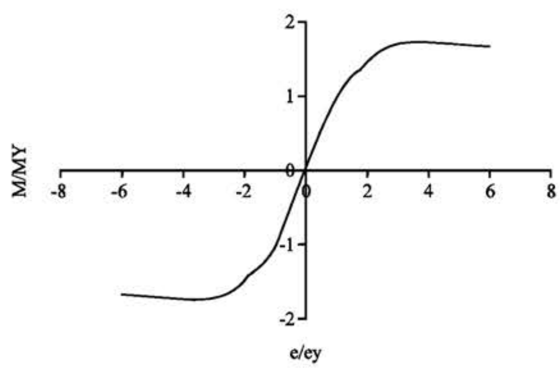

Fig. 24: Moment rotation curve of the modified connection

twelve stories with 3 m height. The frame elements are designed in accordance with the current regional code of seismic practice. Two different joint elements were defined and assigned to the element ends to reflect the original and the modified connection moment rotation behavior. The moment rotation diagrams were generated based on the normalized back bone curves of the hysteretic loops resulted from the finite element analysis.

The normalized moment rotation curves shall be seen in Fig. 23 and 24.

As it is evident from the figures the unmodified connection has an increasing branch after the yield point up to the rotation equal to 3 θy. The moment increases at this branch up to 1.33 My. After this stage significant deterioration is observed, this is mainly due to the premature fracture of the weld roots.

The modified connection behavior is much more stable in comparison with the original connection. The increasing branch continues up to the rotation similar to the original connection, while the moment grows up to 1.71 My. Minor degradation (about 4%) is anticipated after this stage and the connection surrenders a total rotation about 6 θy. Push-over curves are shown in Fig. 25 for different frame models.

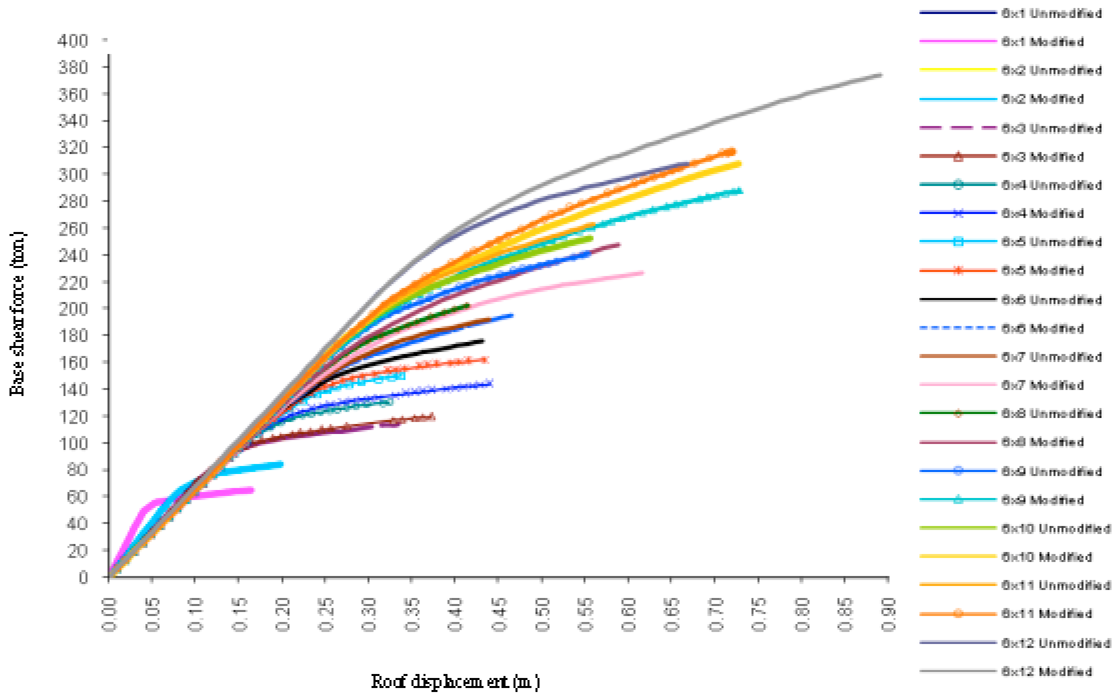

Fig. 25: Base shear-roof displacement curves of frame models

It may be concluded from the results that the connection effect is negligible in frames with three or less number of stories.

In frames with 4 or more stories the connection effect is brilliant and ultimate moment capacities and ductility ratios are significantly improved in modified connection. The ductility of frames varies from 2.00 to 2.50 with an average modification about 35% due to the connection behavior. Also the ultimate moment capacities of the frames are promoted up to 20%.

CONCLUSION

Based on the finite element investigations performed on the full-scale connection models the following conclusions shall be made:

- The thickness of the cover plates and the end plate affects the stiffness and the moment capacity of the connection significantly and hence shall be dimensioned precisely to fulfill the design demands.
- Number and diameter of the holes must lie between the limiting boundaries in order to provide optimized results. The hole diameter shall be limited to 0.80 times the cover plate thickness and the clear distance between holes should not be less 1.25 times the plate thickness to give identical results. These boundaries define a feasible configuration in most possible occasions.
- If a favorable configuration and am proper alignment of holes are considered, significant enhancement is expected. Featuring the required stiffness, the connection delivers the total expected moment capacity with no brittle fracture at weld roots. The rotational ductility is extremely modified (about 60%) regardless of ordinary weld imperfections. The connection is featuring a rotational ductility exceeding 8.00 which is quite satisfactory.
- The connection effect is negligible in low rise frames (less than 4 stories). This effect is amplified by adding the number of stories. Ductility ratio and the relative shear capacity of the frames are improved up to 35 and 20%, respectively. The ductility ratio of the frames vary from 2.00 to 2.50.

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