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Investigation of dual steel frames with rigid and semi-rigid connections

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Professional paper

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Analysis of supported steel frames with rigid and semi-rigid connections

The use of a bracing system for controlling lateral displacement of frames, especially in case of semi-rigid connections, is analysed in the paper. The results indicate that various effects on the stiffness and ductility parameters of structures can be achieved with different bracing methods by the use of rigid connections instead of semi-rigid connections in supported frames. Moreover, the progressive instability of structures can in some cases be influenced.

Key words:
supported frame, rigid and semi-rigid connections, non-linear static pushover analysis

Stručni rad

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Analiza poduprtih čeličnih okvira s nepopustljivim i djelomično nepopustljivim priključcima

U radu je analizirana primjena veznog sustava za kontrolu bočnog pomaka okvira naročito djelomično nepopustljivih priključaka. Rezultati pokazuju da se primjenom nepopustljivih priključaka umjesto djelomično nepopustljivih priključaka u poduprtim okvirima pri raznim metodama stabilizacije postižu raznovrsni utjecaji na parametre krutosti i duktilnosti konstrukcija. Osim toga, u nekim se slučajevima može utjecati i na progresivnu nestabilnost građevina.

Ključne riječi:
poduprti okvir, nepopustljivi i djelomično nepopustljivi priključci, nelinearna statička metoda postupnog guranja

Fachbericht

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Analyse gehaltener Stahlrahmen mit biegesteifen und teilweise nachgiebigen Anschlüssen

In dieser Arbeit wird die Anwendung von Halterungssystemen zur Kontrolle lateraler Verschiebungen analysiert, insbesondere bei Rahmen mit teilweise nachgiebigen Anschlüssen. Die Resultate zeigen, dass durch den Einsatz biegesteifer Anschlüsse anstelle von teilweise nachgiebigen Anschlüssen für gehaltene Rahmen bei verschiedenen Stabilisierungsmethoden unterschiedliche Einflüsse auf die Steifigkeits- und Duktilitätsparameter erzielt werden. Außerdem kann in manchen Fällen die progressive Instabilität der Konstruktion beeinflusst werden.

Schlüsselwörter:
gehaltene Rahmen, biegesteife und teilweise nachgiebige Anschlüsse, nichtlineare statische Pushover Methode

1. Introduction

The behaviour of the beam to rigid/joint column connections is assumed to be complete in conventional methods of steel frame design and analysis. With regard to these assumptions, the design and analysis phases of steel frames are simpler. However, the laboratory results imply an existence of a degree of flexibility in hypothetical rigid connections and a degree of rigidity in hypothetical joint connections. That is why it is essential to consider semi-rigid connections to achieve an accurate analysis and economic design of steel frames. Kabes's and Nutrio's studies on the steel frame behaviour in the earthquakes of 1994 and 1975 prove that a series of damage occurs in the zone of the beam to column connections [1]. According to these analyses, well-designed semi-rigid connections participate in the non-linear behaviour of structures and lead to improvement of seismic behaviour of steel frames with a low and average number of storeys [2]. In a study on the moment resisting frames, it has been shown that semi-rigid connections lead to overall material and frame execution cost savings of around 20 percent [3]. It should be noted that actions such as investigation of great displacements and comparison of these displacements with those of a rigid structure, recommendation of displacement control methods and their evaluation and, finally, study of behaviour of rigid and semi-rigid structures, can contribute to greater use of semi-rigid connections in structures [4].

Although the stiffness of concentric bracings exceeds that of eccentric bracings, the dissipation of energy and ductility of eccentric bracings are higher when compared to concentric bracings [5]. One of the methods for evaluating seismic performance of structures is a non-linear static analysis (pushover). In this method, results are presented in terms of element performance, and the structural components performance is categorized at 3 levels:

According to FEMA 356 [6], the building performance level is defined on the basis of the structural and non-structural performance of components. This level is defined with regard to the amount of cracking or damage of structural and non-structural components. Structural components are elements such as columns, beams, braces, shear walls, diaphragms, bases, and other similar components. The criteria of the structural-components performance level are divided with regard to the type of structural system, primary or secondary member, and transient and permanent lateral drift.

The transient lateral drift means the maximum relative lateral displacement of the storey. It is assumed that such parameter is developed during occurrence of a basic safety earthquake. Moreover, the permanent lateral drift refers to the maximum relative lateral drift of the story which remains in the structure after occurrence of the basic safety earthquake, due to the cracking or plastic behaviour. The performance of structural components has three classifications, which are denoted by a number and the letter S. The immediate occupancy performance level refers to the performance level at which it is predicted that, due to occurrence of an earthquake, the resistance and stiffness of structural components are not altered considerably. Moreover, the permanent deformation and cracks are not developed in the components. Hence, the immediate occupancy of the structure is feasible. At this performance level, the maximum amount of transient lateral drift reaches the value of 0.7 %. This performance level is called S-1. The life safety performance level refers to the performance level at which it is prognosticated that the occurrence of an earthquake will damage the structure, but this damage will not be so huge to cause fatalities. Therefore, the remaining stiffness and resistance of structural components exist at all storeys. The gravity load system is activated and permanent deformations are developed in the structure.

At this level of performance, the values of maximum transient lateral drift and maximum permanent lateral drift are limited to 2.5 % and 1 %, respectively. This performance level is named S-3. The collapse prevention performance level refers to a performance level at which a structure is expected to encounter huge structural damage due to occurrence of an earthquake, but the building will not collapse and the fatality rate will be minimum. So, the remaining stiffness and resistance in structural components will be negligible. Also, as there are so many permanent deformations, the unbraced walls and bumps will be disjointed. With regard to the developed conditions, the building is situated in the collapse prevention state. At this level of performance, the values of maximum transient lateral drift and maximum permanent lateral drift are limited to 5 %. This performance level is named S-5. The immediate occupancy, life safety and collapse prevention performance levels are abbreviated to IO, LS and CP, respectively [6].

Performance levels of primary and secondary members are illustrated in the force-displacement diagram (Figure 1). Performance levels of primary and secondary members are denoted by letters (P) and (S), respectively [6].

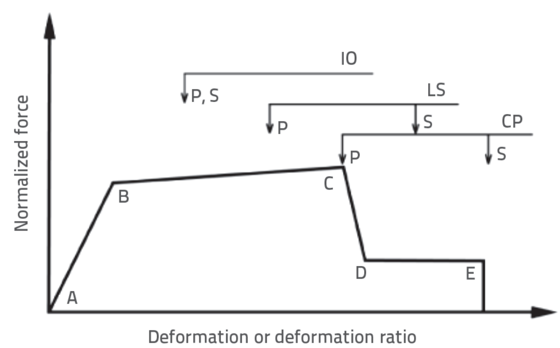

Figure 1. Performance levels of primary and secondary members [5]

The frames were analysed using the PERFORM 3D software [7]. The PERFORM 3D [7] is a software with a special focus on the earthquake-resistant design. The software vendor is CSI Company [7]. Complex structures can be analysed in nonlinear manner on the basis of various resistance limit states and deformation via the PERFORM software. This software has powerful capabilities that can be used for designing based on performance. Also, it can compute capacity/requirements ratios for all components and limit states. Furthermore, this software is able to automatically evaluate performance with regard to FEMA 356 [6].

2. Model features

Four samples are studied in this paper. The first sample includes a dual steel frame with eccentric Inverted v-bracing. The Second sample consists of two dual steel frames with concentric inverted v-bracing. The third sample consists of three dual steel frames with X-bracing, and the last sample consists of four dual steel frames with two-storey X-bracing. Every sample includes two models and, in the first model, the beam to column connection is rigid (RMC). In the second model, the beam to column connection is semi-rigid (SRMC). The performance of semi-rigid connections in available rigid connections, and the design of semi-rigid connections in the first step of the design process, revealed the need for further research in this field. Different types of sections were used throughout the modelling of the structure. The beams, columns and bracing are made of IPE, IPB (HE-B) and UNP sections, respectively, in accordance with German DIN standards. The steel is assumed to be St37.
The materials consisted of mild steel with 2400 kg/cm^2 in yield strength, and 3700 kg/cm^2 in ultimate strength. The resistant anchor and half of the beam plastic anchor (0.5 $M_{pl-beam}$) were utilized in the semi-rigid connection modelling. The values of K_θ and M_{CE} are calculated using equations (1) and (2), respectively.

$$K_0 = \frac{M_{CE}}{0,003} \quad (1)$$

$$M_{CE} = ZF_{y_e} \quad (2)$$

where:
K_θ - rotational stiffness
M_{CE} - denotes the expected bending moment
Z - the basis of plastic section
F_{ye} - the expected yield stress equal to 1.1F_y.

The moment-rotation diagram according to FEMA 356 [6] is used for modelling the moment-rotation behaviour of a semi-rigid connection. To this end, it is assumed that the rotational yield θ_y is equal to 0.003. Modelling parameters and acceptance criterion for semi-rigid connections were determined using FEMA 356 [6]. The plan of all analysed structures is displayed in Figure 2.

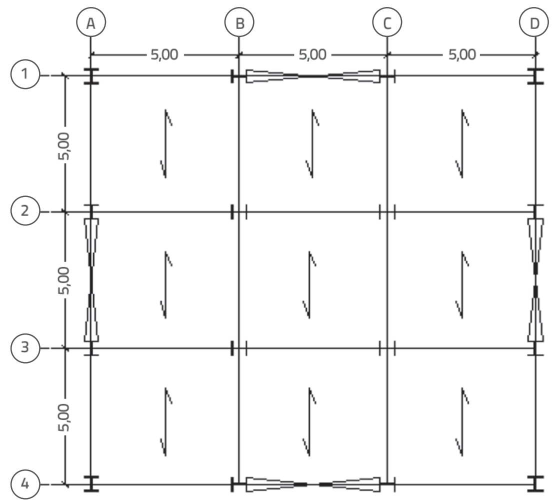

Figure 2. Plan view of analysed structures

The frame that is located on the first and fourth axis is used in non-linear analysis. Its geometry is presented in Figure 3.

These frames are designed according to the AISC-ASD Code. The results are presented in Table 1.

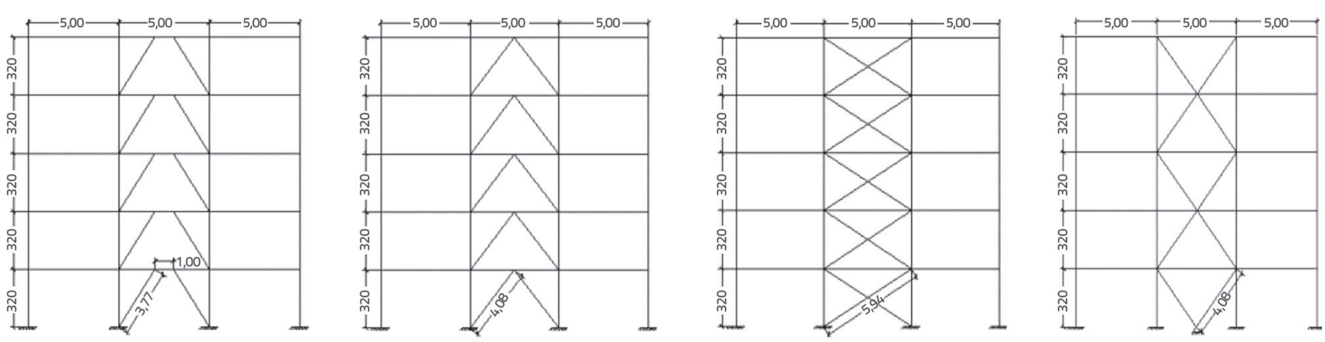

Figure 3. Frame view for different models: a) Dual frame with eccentric Inverted V-bracing; b) Dual frame with concentric Inverted V-bracing; c) Dual frame with X-bracing; d) Dual frame with two storey X-bracing

Table 1. Designed cross-sections of frames

	Storeys	Columns 1-B and 1-C	Columns 1-A and 1-D	Bracings	Beams 1-AB and 1-CD	Beam 1-BC
Dual frames with eccentric inverted V-bracing	1	HE320B	HE240B	2UNP180	IPE300	IPE400
	2	HE260B	HE240B	2UNP180	IPE300	IPE400
	3	HE260B	HE240B	2UNP160	IPE300	IPE360
	4	HE240B	HE220B	2UNP160	IPE270	IPE270
	5	HE240B	HE220B	2UNP120	IPE240	IPE240
Dual frames with concentric inverted V-bracing	1	HE300B	HE200B	2UNP160	IPE300	IPE550
	2	HE240B	HE200B	2UNP160	IPE300	IPE550
	3	HE220B	HE180B	2UNP160	IPE270	IPE500
	4	HE220B	HE180B	2UNP140	IPE270	IPE450
	5	HE220B	HE180B	2UNP120	IPE270	IPE400
Dual frames with X-bracing	1	HE360B	HE180B	2UNP140	IPE300	IPE300
	2	HE280B	HE180B	2UNP140	IPE300	IPE300
	3	HE220B	HE180B	2UNP120	IPE300	IPE300
	4	HE180B	HE180B	2UNP120	IPE300	IPE300
	5	HE180B	HE180B	2UNP100	IPE270	IPE270
Dual frames with two storey X-bracing	1	HE360B	HE200B	2UNP180	IPE300	IPE300
	2	HE240B	HE200B	2UNP180	IPE300	IPE300
	3	HE220B	HE180B	2UNP160	IPE300	IPE300
	4	HE180B	HE180B	2UNP140	IPE300	IPE300
	5	HE180B	HE180B	2UNP100	IPE270	IPE270

2.1. Sample 1: Modelling dual frame with eccentric Inverted V-bracing

The pushover diagram, structure displacement within the target displacement, and the performance levels of members, were studied, after applying the pushover analysis, on the dual frame with eccentric inverted v-bracing. By comparing the pushover diagram shown in Figure 4, it becomes clear that the replacement of rigid connections with semi-rigid ones reduces the gradient of the diagram in the linear and non-linear areas, which indicates the stiffness reduction of the frame within linear and non-linear areas. The value of stiffness related to the linear region has decreased from 18069.8 kN/m for rigid frame to 14868.2 kN/m for semi-rigid frame, and the percentage of reduction is equal to 21.53 %. In the non-linear region, the stiffness reduction rate is higher. Also, the lateral yield resistance has reduced from 777 kN/m to 722 kN/m, which is a 7.6 % decrease.

The ultimate resistance limit has decreased from 1107 kN to 966 kN, which is a 14.6 % reduction. There is no significant change in frame ductility with regard to the investigation of yield displacement. Both models appear as a mechanism within the same displacements.

By making a comparison between drift diagrams for storeys (Figure 5), it can be claimed that the story drift ratio on the lower and upper floors corresponding to target displacement has increased due to

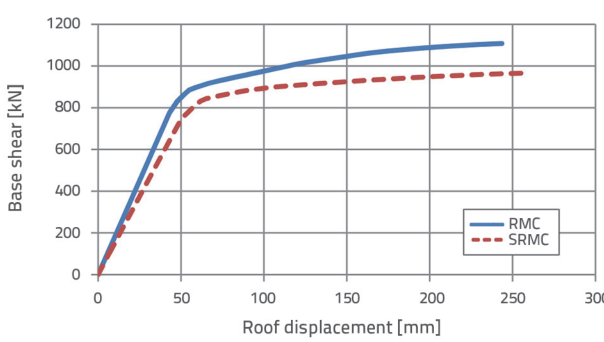

Figure 4. Comparison of pushover curves in eccentrically Inverted V-braced frame

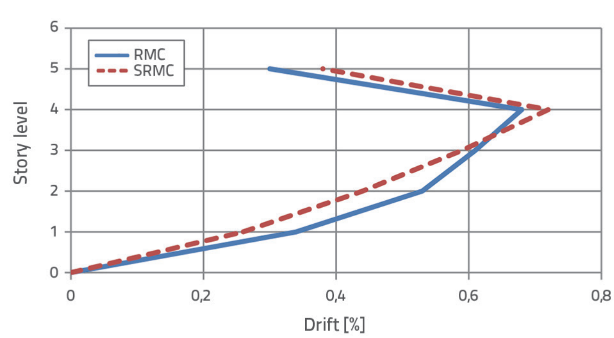

Figure 5. Comparison of storey drift ratio for frame with eccentric Inverted V-bracing

the replacement of rigid connections with semi-rigid ones. The frame with rigid connections and maximum lateral displacement of 0.68 % is located within the range of immediate occupancy level, and the frame with semi-rigid connections and maximum lateral displacement of 0.72 % passes beyond this range.

The comparison of performance levels given in Figure 6 confirms the fact that more beams will enter the ranges of IO-LS and LS-CP by the replacement of rigid connections with semi-rigid connections.

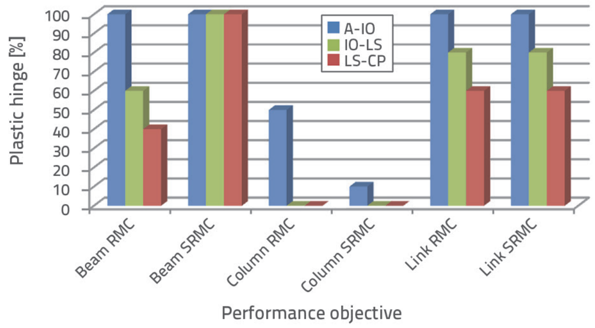

Figure 6. Comparison of performance levels of members in dual frames with eccentric Inverted V-bracing

2.2. Sample 2: Dual frame with concentric Inverted V-bracing

After the pushover analysis, the pushover diagram, structure displacement within the target displacement, and the performance levels of members, were studied on the dual frame with concentric inverted v-bracing. By comparing the pushover diagram shown in Figure 7, it can be seen that the ductility increases and the yield strength decreases, which is due to the replacement of rigid connections with their semi-rigid counterparts. The stiffness of the frame did not change considerably. The ductility coefficient of the frames with rigid and semi-rigid connections amounted to 1.77 and 2.1, respectively, and the rate of increase was 18.6 %. The lateral yield resistance of rigid and semi-rigid frames amounted to 1237 KN and 1158 KN, respectively, and the decrease rate was 6.8 %.

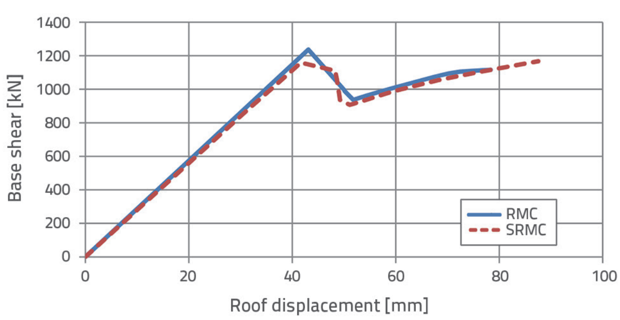

Figure 7. Comparison of pushover curve of frame with concentric Inverted V-bracing

The comparison of story drift ratio diagram shown in Figure 8 shows an increase of the story drift ratio corresponding to the target displacement on the lower floor and its stability on the upper floor, and all these conditions are due to the replacement of rigid connections with semi-rigid ones. A frame with rigid and semi-rigid connections with lateral drift ratios of 0.64 % and 0.6 % on the first floor, is located within the immediate occupancy range.

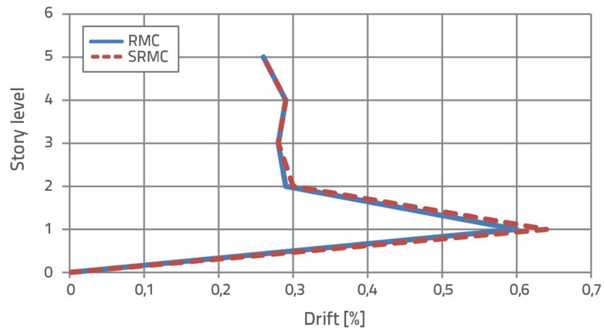

Figure 8. Comparison of storey drift ratio in frame with concentric Inverted V-bracing

By comparing the performance levels diagram shown in Figure 9, it can be seen that the utilization of semi-rigid connections leads to the introduction of more beams into the ranges of A-IO, IO-LS and LS-CP.

The performance of columns remains constant and, in both models, the column does not reach the range of LS-CP. On the first and second floors, the condition of the columns that are located near bracings is critical. In addition, the performance of the bracings remains stable in spite of using semi-rigid connections and, in both samples, the same percent of joints is formed within the LS-CP, IO-LS, and A-IO ranges.

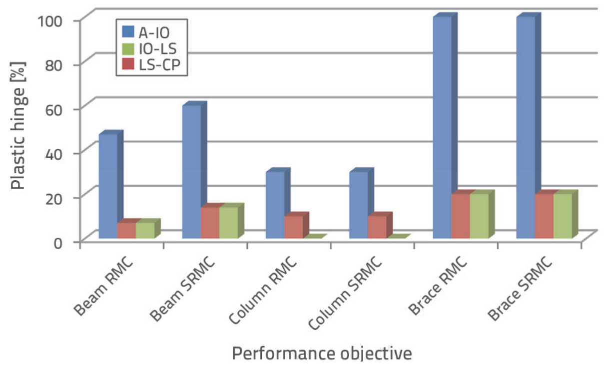

Figure 9. Comparison of performance levels for frame with concentric Inverted V-bracing

2.3. Sample 3: Modelling dual frame with X-bracing

By comparing the pushover diagram (Figure 10), it can be deduced that, because of the use of X-braces and their high stiffness, the change from rigid connections to semi-rigid connections results in a slight decrease in resistance and stiffness parameters, while ductility remains stable.

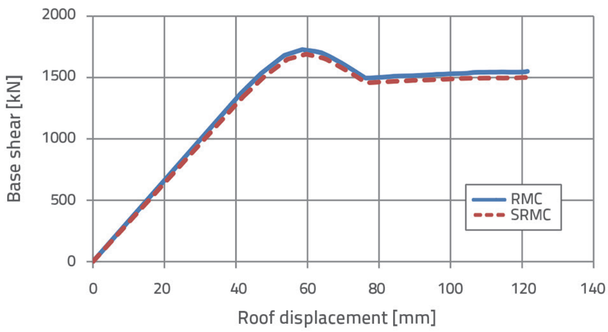

Figure 10. Comparison of pushover curve in frame with X-bracing

The comparison of the story drift ratio presented in Figure 11 shows that the story drift ratio of the floor corresponding to the target displacement increases if semi-rigid connections are used instead of rigid connections. The rate of maximum displacement for frames with rigid and semi-rigid connections is equal to 0.32 % and 0.33 % and the frames with the mentioned displacements are located within the immediate occupancy range.

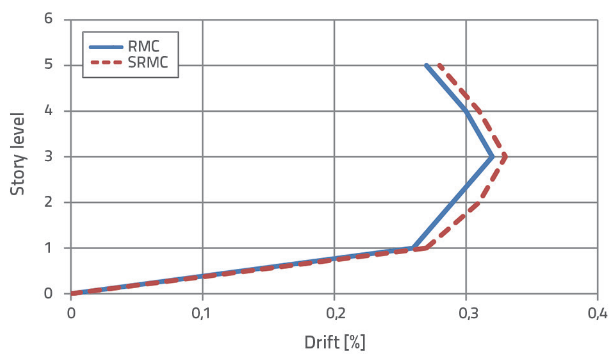

Figure 11. Comparison of story drift ratio in frame with X-bracing

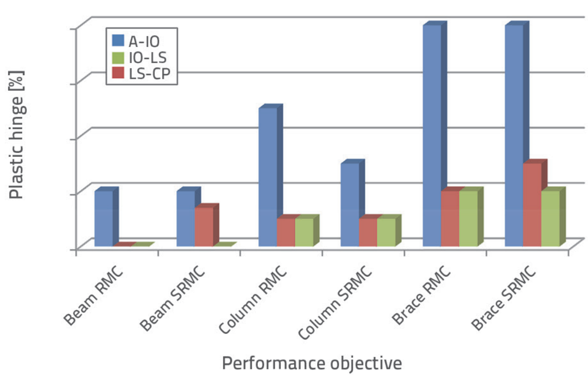

Figure 12. Comparison of performance levels for frame with X-bracing

By comparing performance levels given in Figure 12, it becomes clear that the use of semi-rigid connections leads to the introduction of more beams into the IO-LS range, while no beam reaches the LS-CP range. The number of columns located within the A-IO range reduces but the number of the columns within the IO-LS and LS-CP ranges remains constant. A greater number of bracings enters into the IO-LS range due to the use of semi-rigid connections. The number of bracing members that enter the LS-CP range remains unchanged.

2.4. Sample 4: Modelling a dual frame with two storey X-bracing

The displacement of the structure within the target displacement, and performance levels of the members, were investigated after application of the pushover analysis on the dual frame with two storey X-bracing. By comparing the pushover diagram (Figure 13), it can be construed that the values of resistance, stiffness and ductility change due to change from rigid connections into the semi-rigid connections, and the frame with semi-rigid connection reaches instability sooner. By using pushover diagram, it can be deduced that the ductility value of the frame with rigid and semi-rigid connections equals 2.88 and 2.34, respectively, which corresponds to the reduction in ductility of about 1.23 %.

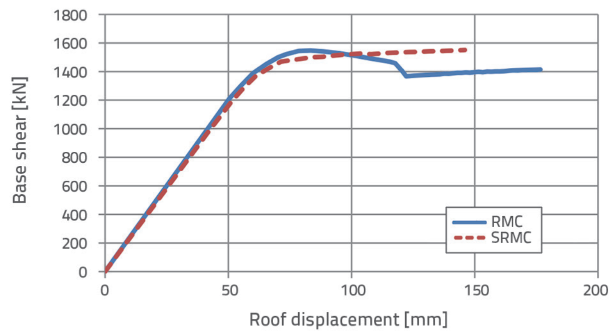

Figure 13. Comparison of pushover curve for frame with two storey X-bracing

By comparing the storey drift ratio diagram shown in Figure 14, it becomes clear that the story drift ratio corresponding to the target displacement increases by using semi-rigid connections instead of rigid connections. Thus the frames with rigid and semi-rigid connections having the drift ratio of 0.48 % and 0.5 %, respectively, are located at the range of immediate occupancy level.

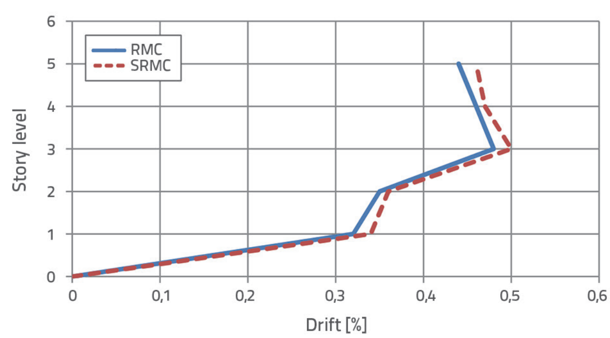

Figure 14. Comparison of drift ratio for frame with two storey X-bracing

By comparing performance levels shown in Figure 15, it becomes clear that, due to replacement of rigid connections with semi-rigid connections, the number of beams entering the A-IO range remains constant and more beams are situated at the ranges of IO-LS and LS-CP. In a semi-rigid frame, less columns are located within the A-IO range, and there is no column at IO-LS and LS-CP ranges. More bracing members enter the IO-LS range during the use of semi-rigid connections, and the number of bracing members located at the A-IO and LS-CP ranges remains unchanged.

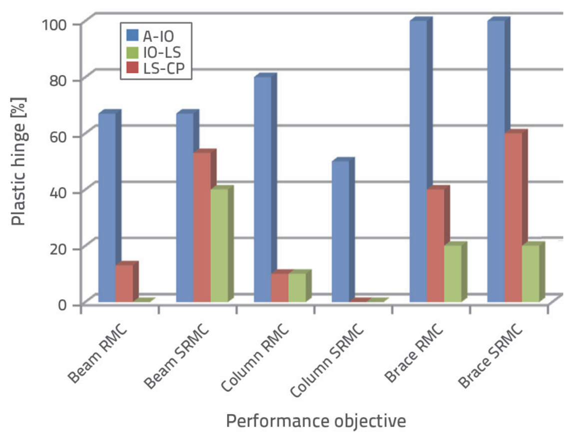

Figure 15. Comparison of performance levels for frame with two storey X-bracing

2.5. Analysis of modelling results

Analysis of example 1

In case of dual frame with eccentric Inverted V-bracing, the moment of the frame is considerably influenced by lateral force as the bracings are eccentric. As a result, replacement of rigid connections with semi-rigid ones has a considerable effect on the behaviour of structures. Generally speaking, it seems that the behaviour of eccentrically braced frames (EBFs) is desirable, since the diagram elongation, along with hardening in the non-linear area, leads to improved behaviour of the frame consisting of rigid connections.

Since the substitution of rigid connections for semi-rigid connections also results in greater rotation of the connection, it is expected that an increase in structural displacement will be observed, but the lateral displacement of dual frame reduces via bracings. This is considered to be an advantage of these frames, especially when they consist of semi-rigid connections.

Some lateral displacement is permitted In this sample, due to low stiffness of the eccentric inverted V-bracing and early plasticization of the link beam.

The column performance becomes better due to the mentioned replacement and so about 10 % of these columns are located in the A-IO range. The performance of the link beam remains stable at the ranges of A-IO, IO-LS, and LS-CP because of the use of semi-rigid connections; 80 % and 60 % of these beams are located within the IO-LS and LS-CP ranges, respectively.

The bending moment of the semi-rigid connections increases in case of gravity load, when compared to rigid connections. By replacing rigid connections with semi-rigid ones, lateral load upon the beams decreases and the effect of the gravity load increases. it is therefore essential to reinforce the beam. Generally, a small amount of lateral forces is imposed on the beams because of replacement of rigid connections with semi-rigid ones, while the portion imposed on the braces increases. With regard to the strong column weak beam principle, and due to the fact that the beams are essential components, it is desirable to employ semi-rigid connections instead of rigid connections during construction of moment structures. In an eccentric system, the nonlinear behaviour and plasticization of link beams are expected as a result of energy depreciation, which is in accordance with the obtained results. The performance of braces is similar in both models and none of the components enters extremal regions.

Analysis of example 2

Generally, the behaviour of the frame with concentric inverted V-bracing is not so ductile. The ductility of the frames increases to some extent and the frame instability is postponed. All this results from the use of semi-rigid connections, which allows considerably greater rotation of the connections.

A big portion of the frame resistance in this model is provided by bracings and the use of semi-rigid connections does not impact lateral resistance and lateral stiffness considerably. In these two models, a sudden decrease of resistance after the yielding strength has been reached is principally due to the buckling of compressive braces on the first and second floors.

As rigid connections are converted to semi-rigid connections, the stiffness of the frames will decrease. In this system, the stiffness of bracings is higher than the stiffness of bracing frame and via this model the structure behaviour will be controlled. After the yield strength and sharp decline in resistance, a hardening is observed in the non-linear region.

In this model, thanks to high lateral stiffness of the bracings, the use of semi-rigid connections did not impact displacements considerably. The concentric inverted bracing increases stiffness of the dual frame, and it also controls the displacements due to the fact that this bracing's cross-section is greater in comparison with other concentric bracings.

Gravity loads will increase the bending moment of the beam in semi-rigid connections compared to rigid connections. The use of semi-rigid connections will also reduce influence of lateral loads on the beams and increase the impact of gravity loads. The beam size is expected to increase, since the beams to which bracings are attached, after the buckling of compressive braces, must tolerate a great unbalanced force resulting from an earthquake.

For these beams, a bending plastic joint can be created at any point along the beam except at two ending points. By converting rigid connections into semi-rigid connections, the condition of the beams becomes more critical. The influence of lateral force on bracings increases, and the frame stiffness decreases.
However, due to some brace design criteria, even the use of semi-rigid connections does not influence performance of the bracings considerably. The frame will have brittle behaviour and it will become instable prior to the formation of expected joints.

Analysis of example 3

In modelling the dual frame with X-bracing, the stiffness of the x-bracing is high. As a result, the behaviour of the frame does not change considerably regardless of the use of semi-rigid connections. In terms of resistance drop due to yield strength, the behaviour of this frame is similar to that of sample 2, which is equipped with a concentric Inverted V-bracing. The main reason for resistance drop is the buckling of compressive braces on the first and second floors. Even by converting rigid connections to semi-rigid ones, this resistance drop is not excluded, and an earlier formation of resistance drop can be expected due to high influence on the bracings, compared to gravity loads. In a concentric Inverted v-bracing, the plastic axial joint is being formed in the bracings, which is the same for two models. By formulation of plastic joints and their development, the mechanization of the both models will coincide. It can be deduced that in the dual frame with X-bracing, the use of semi-rigid connections will not have a high influence on the resistance, stiffness and ductility parameters. The behaviour of dual frame with X-bracing is better than the behaviour of dual frame with the concentric inverted V-bracing (Sample 2). Seemingly, the use of semi-rigid connections in X-braced frame is recommended.
In this model, due to existence of high lateral stiffness of the bracings, the use of semi-rigid connections will not change the displacements considerably. By converting rigid connections to semi-rigid ones, the stiffness of the frame decreases and the drift ratio increases. The bracings of the upper floors are more prone to displacement alteration as the reduction in resistance and stiffness of the moment frame is realized due to the use of semi-rigid connections.
In the case of semi-rigid connections, the beam bending moment due to gravity load increases in comparison with rigid connections. The use of semi-rigid connections decreases the impact of lateral force on the beams, while the impact of gravity loads increases. Thus, the beam strength should be increased, and it would be advisable to investigate the condition and status of the connections. By changing connections, the performance of the columns improves due to reduced impact of lateral load on columns. The effect of lateral force on the bracings increases due to semi-rigid connections and reduction in frame stiffness.
However, because of certain brace design criteria, the performance of the bracings does not change considerably due to use of semi-rigid connections.

Analysis of example 4

In the frame with concentric Inverted V-bracing, unbalanced force is generated within the upper beam due to the buckling of the compressive member, which results in the beam size increase and weak behaviour of the frame. Seven and eight bracing methods can be used in combination to decrease this force. This method is efficient because it leads to an increase in resistance and ductility, in comparison with the sample 2. In the dual frame with two story X-bracings, the lateral resistance at yield point has had a little reduction of about 2 % regardless of the use of semi-rigid connections. In this example, proper performance of bracings has led to negligible variation of resistance due to replacement of connections. A small frame stiffness reduction in linear region was observed when the semi-rigid connection was used. But, the stiffness of the frame has decreased in the non-linear region. However, an increase in stiffness can be observed in the frame with semi-rigid connections. A frame with semi-rigid connections was converted to a mechanism sooner than a frame with rigid connections. Thus, its ductility has decreased.
Due to proper arrangement and appropriate lateral stiffness of bracings, no considerable displacements have been noted after conversion of rigid connections to semi-rigid ones. The use of semi-rigid connections has decreased the frame stiffness, while lateral displacements have increased. The bracings are more prone to displacement on the upper floors due to reduction of resistance and moment frame stiffness, resulting from the use of semi-rigid connections.
It is therefore necessary to increase the beam size and apply reinforcement measures to strengthen the beam.
In the case of semi-rigid connections, the bending moment of the beam increases in comparison with rigid-connections, which is due to the influence of gravity load. By the use of semi-rigid connections, the influence of lateral load on the beams decreases, while the influence of gravity load increases. Better performance of the beams on eight bracings or seven bracings was observed in case of the two story x-bracing. The second bracing neutralized the unbalanced force to some extent, which induced a proper behaviour in rigid and semi-rigid modes. By changing the connections, the performance of the beams has improved due to low influence of lateral load on the beam.
The influence of lateral force on the bracing increased due to use of semi-rigid connections and by reduction of frame stiffness. But, due to some brace design criteria, the performance of the bracings did not vary significantly as a result of the use of semi-rigid connections.

3. Conclusions

The use of semi-rigid connections is recommended as a measure to improve insufficient ductility of rigid connections. The high value of lateral drift of a frame with semi-rigid connections should be considered as a drawback, which can be resolved by adding a bracing system. Thus, the behaviour of semi-rigid frames with braces is studied, and the obtained results are summarized as follows:

- In a dual frame with eccentric inverted V-bracing, the change from rigid connections to semi-rigid connections has caused considerable decrease of resistance and lateral stiffness. There is no significant change in the ductility of frames. The lateral drift was increased and the need arose to increase the beam resistance. Therefore, the use of semi-rigid connections in dual frame necessitates high resistance and stiffness. In general, this frame is more sensitive to the use of semi-rigid connections, compared to sample 3.
- In a dual frame with concentric inverted V-bracing, the change from rigid connections to semi-rigid connections has caused an increase in ductility, and it has postponed instability of the frame. The lateral drift has increased. The resistance of beam components (connected to braces) is sufficient, except in limited cases. It can be claimed that the system behaviour has been improved.
- In a dual frame with x-bracing, the change from rigid connections to semi-rigid connections causes no significant change in the values of stiffness, resistance and ductility. The value of lateral drift has increased slightly, and a limited number of beams and braces need to be enhanced in terms of resistance. Generally, this frame is less sensitive to the use of semi-rigid connections, compared to sample 3.
- In a dual frame with two storey X-bracing, the instability of the frame happens earlier and ductility decreases after substitution of semi-rigid connections for rigid connections. The lateral drift has increased slightly. In this case, a great number of beams and a limited number of braces should be enhanced in terms of resistance.

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