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Investigation of nonlinear behaviour of reinforced concrete frames having different stiffening members

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Abstract. The selected carrier systems of reinforced concrete frame buildings are quite important on structural damages. In this study are examined comparatively nonlinear behaviours of reinforced concrete frames which having different stiffening members under a horizontal load. In that respect, the study consists of six parametric models. With this purpose, nonlinear structural analyses of reinforced concrete frames which having different stiffening members were carried out with LUSAS which uses the finite element method. Thus, some conclusions and recommendations to mitigate the damage of reinforced concrete buildings in the future designs are aimed to present. The obtained results revealed that in terms of performance, the x-shaped diagonal elements can be used as an option to shear walls. In addition, it was found that frame-2, frame-3 and frame-4 showed a better performance than traditional frame system (frame-1).

Keywords: different stiffening members; finite element method; nonlinear analysis

1. Introduction

A large amount of the existing building stock in Turkey which is situated in active earthquake zone almost all of the territory is made of the reinforced concrete frame systems. It is seen that the recent earthquakes which have occurred in the Turkey were damaged to beyond to the acceptable limits in many reinforced concrete building (Scawthorn and Johnson 2000, Adalier and Aydingun 2001, Saatcioglu *et al*. 2001, Sezen *et al*. 2003, Spence *et al*. 2003, Doğangün 2004, Arslan and Korkmaz 2007, Di Sarno *et al*. 2013, Korkmaz *et al*. 2013). Hence, it is clear that it is necessary to take into account horizontal loads such as earthquakes in the design of reinforced concrete frame buildings. In this context, for the architectural and static requirements, it can be necessary to design different forms of reinforced concrete carrier systems. Because traditional frame systems under horizontal loads do not generally have sufficient capacity to resist and they need to be strengthened. With this purpose, the traditional reinforced concrete frame systems (column-beam) are added to carrier systems in the various forms (Rosenblueth 1980, Ambrose and Vergun 1985, Dowrick 1987, Pubal 1988). Thus, ductility, stiffness and strength of the traditional reinforced concrete frame systems increase. In this regard, the some studies relevant to different reinforced concrete carrier systems have been conducted by various researchers (Lee and Basu 1992, Ayvaz

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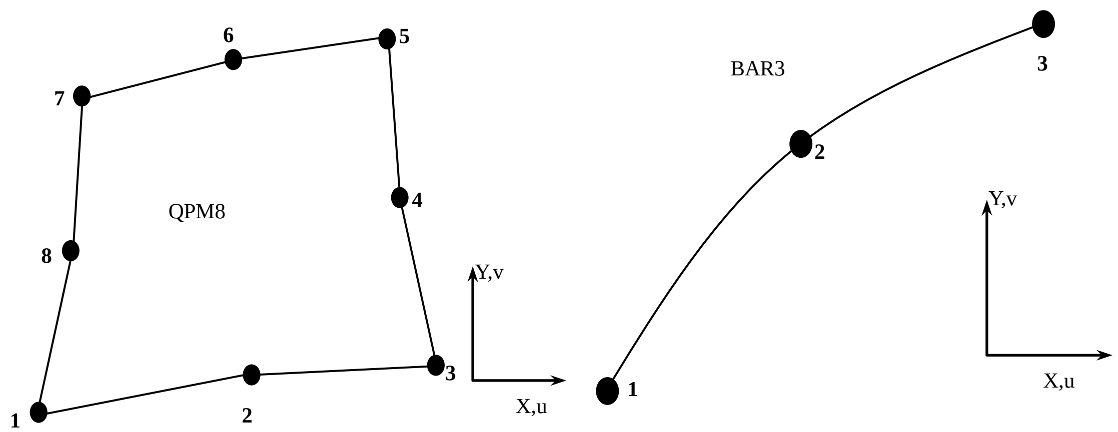
et al. 1997, Hindi and Hassan 2004, Gürsoy and Doğangün 2008, Özdemir and Ayvaz 2008, Kim *et al*. 2009, Durucan and Dicleli 2010, Di Sarno and Manfredi 2010, Vaseghi Amiri *et al*. 2011, Di Sarno and Manfredi 2012, Gürsoy 2013, Carvalho *et al*. 2013). Here, it should be noted that there are advantages and disadvantages of each reinforced concrete carrier systems. This study has focused on the results which are related to the nonlinear analysis of different reinforced concrete carrier systems under horizontal load by using the finite element method.

The last two decades there has been a rapid development of the knowledge in analysis and design of reinforced concrete (RC) structures. Especially, developments in computer programming and numerical methods enabled more detailed and comprehensive investigation of nonlinear analyses. With this purpose, various rational approaches which are based on the inelastic materials behavior have proposed (LUSAS 2006a).

This paper presents a comparative study upon nonlinear analysis of six RC planar frame models having different stiffness members under horizontal load. Thus, it was aimed to provide results to researchers and practitioners about the lateral load performance and the nonlinear behaviour of frames having different stiffening members by examination of the findings obtained from the structural analyses.

The nonlinear behaviour of these RC frames have been examined comparatively with the aid of structural analysis program LUSAS (LUSAS 2006b). The nonlinear behaviour of the concrete and steel was modelled by using cracking concrete model and Von Mises yield criteria that were contained within LUSAS software, respectively. During the modelling, appropriate material properties have been used. With this purpose, eight-node element QPM8 (2D plane stress continuum isoparametric element) was used in the modeling of concrete. This element has eight nodes with two degrees of freedom at each node (translations in the nodal x and y directions; Fig. 1a) and model is capable of cracking, crushing and creep. Reinforcing steel has been modelled by using BAR3 element. BAR3 is an element (uniaxial tension-compression element) with two degrees of freedom at each node (translations in the nodal x and y directions; Fig. 1b). Initial uniaxial yield stress of steel is considered to be 300 MPa. Geometry of the elements (QPM8 and BAR3) is shown in Fig. 1.



(a) 2D plane stress continuum element (b) 2D bar element

Fig. 1 Geometry of elements: (a) QPM8 element and (b) BAR3 element

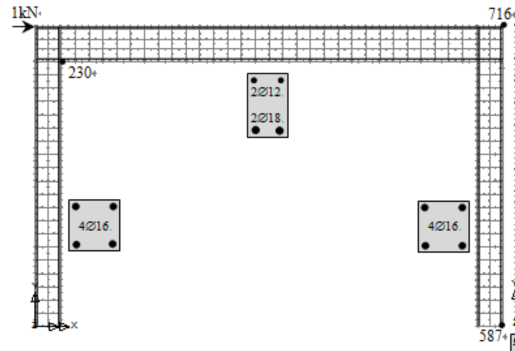
2. Numerical example

Although the concrete frame systems are used widely under vertical loads, they may be insufficient in terms of strength and stiffness under lateral loads such as earthquakes. In this study, the nonlinear behaviours under a horizontal load in models of reinforced concrete frames having different stiffening members have been examined. Thus, the important one in design is to understand the effect of the stiffening components better. This examination is done by considering six parametric models for a horizontal load. With this purpose, a concentrated horizontal load is applied from the left-top of the frame models, and it is assumed that the self weight of the model frames is negligible compared with the applied load. In this example, the concrete section is represented by plane stress (QPM8) elements, and the reinforcement bars (steels) are represented by BAR3 elements. On the other hand, in the LUSAS, nonlinear concrete cracking material model will be applied to the plane stress elements and Von Misses yield criteria will be applied to the reinforcement steels.

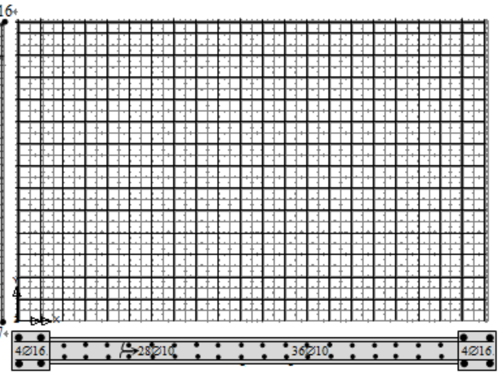
Reinforced concrete frame models considered in this study are shown in Fig. 2. All RC frames shown in this figure have one bay and the heights of all frames are 3.40 m. Also, the span length of the bay was taken as 5 m. All frame models are designed with C35 concrete class and S420 steel class according to requirements for design and construction of reinforced concrete structures (TS500 2000). The other parameters considered in the nonlinear structural analyses are summarized in Table 1.

Table 1 Project parameters of considered frames models

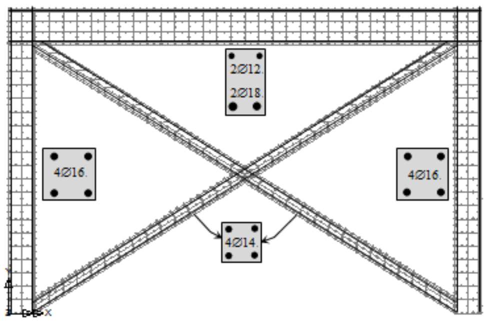
Concrete class (C)	C35
Steel class (S)	S420
Story height (m)	3,40
The cross-sectional dimensions of columns (mm)	300x300
The cross-sectional dimensions of beams (mm)	250x400
The cross-sectional dimensions of diagonal components (mm)	250x250
Thickness of the shear wall (mm)	200
Young's modulus of concrete, E_c (N/mm^2)	33000
Poisson's ratio of concrete, υ_c	0,20
The concrete cover in all reinforced concrete elements (mm)	25
Concrete compressive strength, f_c (N/mm^2)	35
Tensile strength of concrete, f_t (N/mm^2)	2,1
Strain at peak compressive stress, ε_{cp}	0,002
Strain at end of softening curve of concrete, ε_{cu}	0,0025
Strain at end of tensile softening curve, ε_{tu}	0,002
Young's modulus of steel, E_s (N/mm^2)	210000
Poisson's ratio of steel, υ_s	0,30
Initial uniaxial yield stress of steel, f_y (N/mm^2)	300
Ultimate yield stress, $f_{y\,max}$ (N/mm^2)	340
Hardening gradient, (N/mm^2)	2121
Strain at end of hardening curve, ε_{su}	0,02



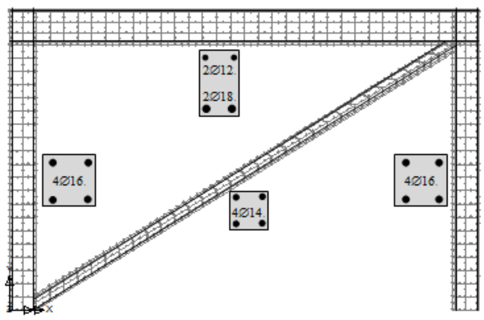
frame-1



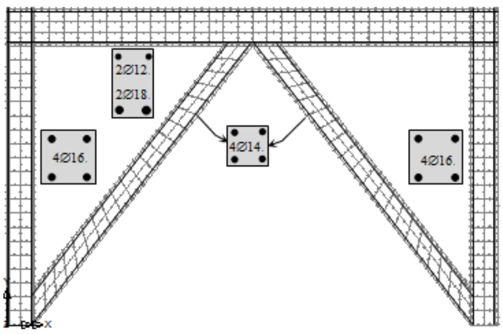
frame-2



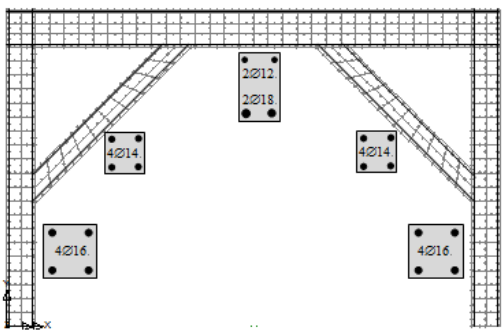
frame-3



frame-4



frame-5



frame-6

Fig. 2 View of the models considered in this study

It should be noted that the cross-section dimensions of the beams, the columns and bracing components in the considered frames are taken as constants.

The behaviour of concrete under compression and tension stress is shown in Fig. 3. The uniaxial tensile strength of steel reinforcement bar has been modelled according to Fig. 4. On the other hand, the nonlinear analyses have been carried out with a starting loading factor of 1000 N. Also, the increase in load factor is 1000 N.

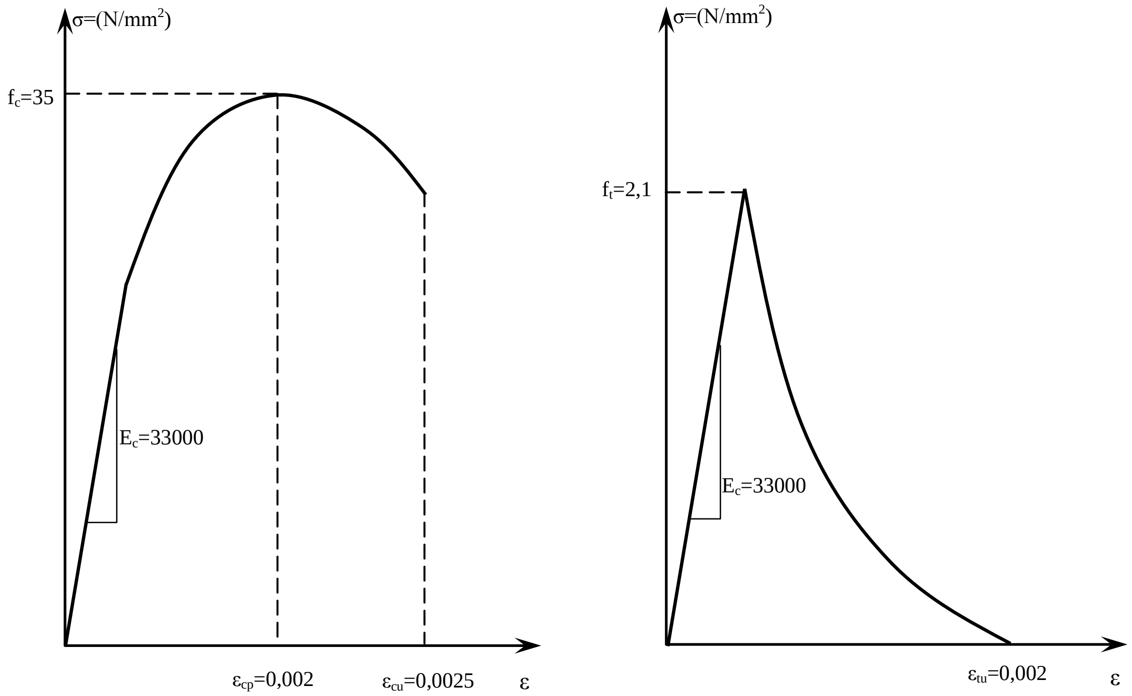


Fig. 3 Compressive and tensile behaviour of the concrete (LUSAS 2006)

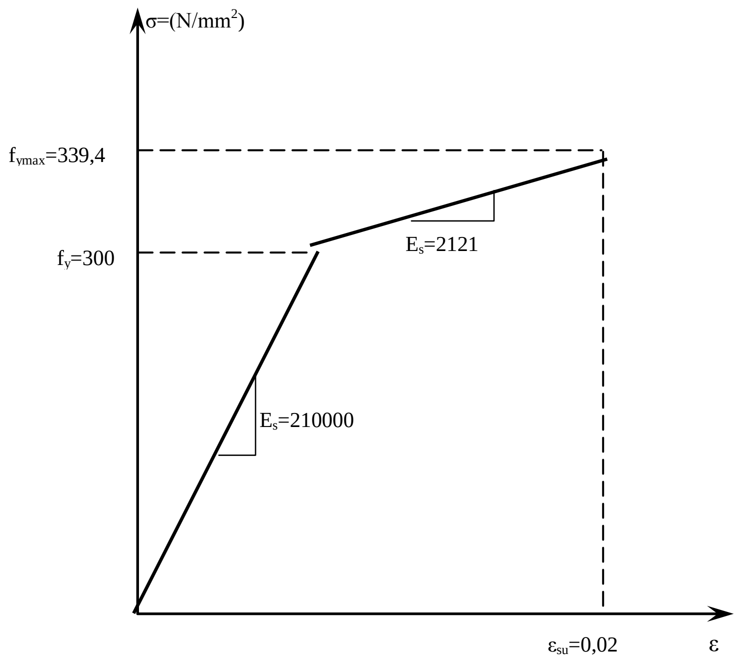


Fig. 4 Behaviour of steel reinforcement bar (LUSAS 2006)

3. Findings and evaluations

The maximum equivalent stresses ($\sigma_E=[\sigma_x{}^2+\sigma_y{}^2+\sigma_z{}^2-\sigma_x\sigma_y-\sigma_y\sigma_z-\sigma_z\sigma_x+3(\sigma_{xy}{}^2+\sigma_{yz}{}^2+\sigma_{zx}{}^2)]^{½}$) and initial crack stresses which obtained from nonlinear analysis are given in Figs. 5-10, respectively.

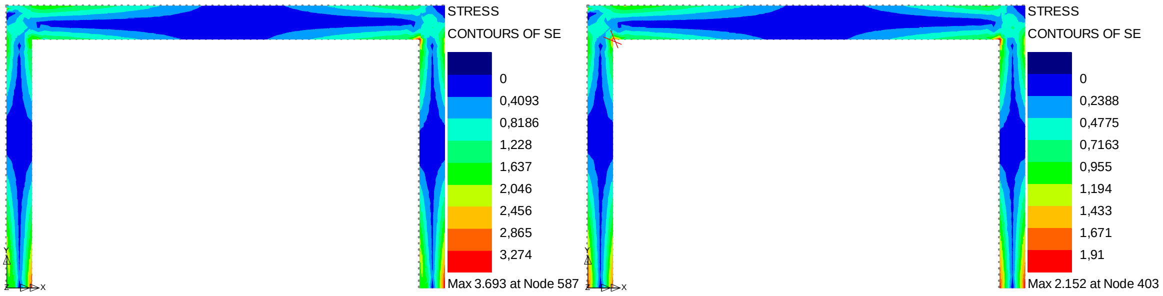
As seen from these figures, different maximum equivalent stress values for frames having diverse stiffening members were obtained. In general, values of equivalent stress obtained from frame 1 gave smaller values than the others. On the other hand, as distinct from other frames, the maximum stress values of the frames having different stiffening members (frame 3, frame 4, frame 5 and frame 6) occur in diagonal elements. This finding reveals that the frames having different stiffening members are better than the other frames. Because, the diagonal elements reduce the damage in basic structural elements such as beams and columns. In other words, damages in the main structural system by sacrificing themselves are prevented. Also, from these figures, it is seen that the initial cracks in the frames having different stiffening members occur in the diagonal elements. In addition to these, value of the maximum equivalent stress at the initial cracks occurring in the frame 2 is greater than the other frames. In other words, frame 2 is the most rigid one.

Here, it should be noted that frame 2 makes the building structure very heavy. These systems from this point of view are not suitable economically and cannot provide safety for the whole structure in earthquakes. Therefore, the stiffened frames with the x-shaped diagonal elements can be a choice without making the building structure heavy.

Maximum equivalent strain ($\varepsilon_E=[\varepsilon_x{}^2+\varepsilon_y{}^2+\varepsilon_z{}^2-\varepsilon_x\varepsilon_y-\varepsilon_y\varepsilon_z-\varepsilon_z\varepsilon_x+0{,}75(\gamma_{xy}{}^2+\gamma_{yz}{}^2+\gamma_{zx}{}^2)]^{½}$) contours obtained from performed analyses of the frames are given in Figs. 11-16, respectively. From these figures, values of equivalent strain obtained from frame 1 give smaller values than the others. Also, as distinct from other frames, the maximum strain values of the frames having different stiffening members are seen to occur in diagonal elements. In other words, the diagonal elements decrease strains in basic structural elements such as beams and columns. This finding reveals that, the frames having different stiffening members are very well behaved.

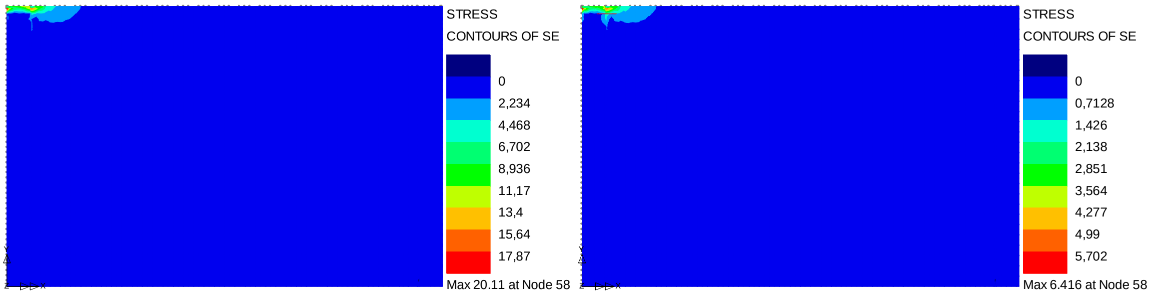
Maximum horizontal displacements contours obtained from nonlinear analysis of the frames are given in Figs. 17-22, respectively. From these figures, as it is expected, value of the maximum horizontal displacement obtained from frame-1 is greater than other frames. As a result, frame-1 shows the worst performance among the considered models. Also, it is seen that the values of maximum horizontal displacement obtained from other frames, except frame 3, 4 and 5, occurred at the top node points. On the other hand, as distinct from other frames, values of the maximum horizontal displacement obtained from frame 3, 4 and 5 occur in the diagonal elements. This finding reveals that, the diagonal elements reduce displacements in basic structural elements such as beams and columns. In other words, the top node points' displacement values get reduced by creating too many load paths. This finding reveals that, the frame 3, 4 and 5 are very well behaved.

The change of horizontal displacements with horizontal loading at the 716 node point of the frames in this study is given in Fig. 23. From this figure, it is seen that horizontal displacement values obtained from frame-2 are smaller than the ones obtained from other models. Besides, horizontal loading of frame 2 and 3 is larger than the ones obtained from other models. This means that the frame-2 behaves in a rigid manner. Also, while horizontal loading in all models are getting increased, the horizontal displacements at the 716 node-point increase as well. On the other hand, it is seen that horizontal displacement of the frames having different stiffening members reduces. This result also reveals that there is a contribution to the performance of basic structural elements such as beams-columns of the additional stiffness members. Also, horizontal displacement values



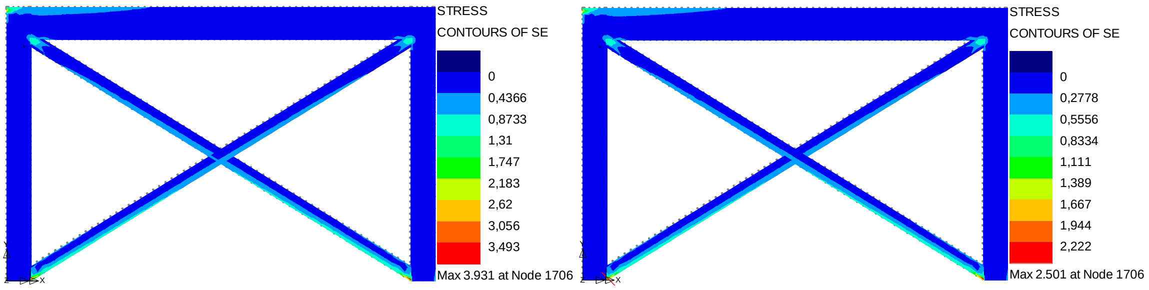
(a) Maximum equivalent stresses (b) Occurring initial crack and stresses

Fig. 5 Maximum equivalent stresses and occurring initial cracks in the frame-1



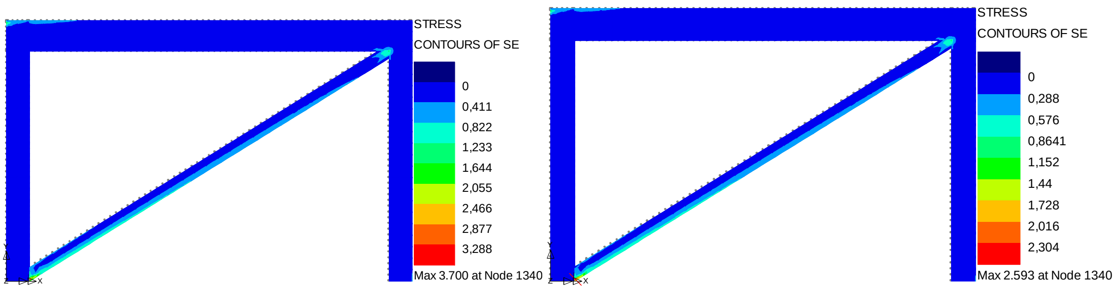
(a) Maximum equivalent stresses (b) Occurring initial crack and stresses

Fig. 6 Maximum equivalent stresses and occurring initial cracks in the frame-2



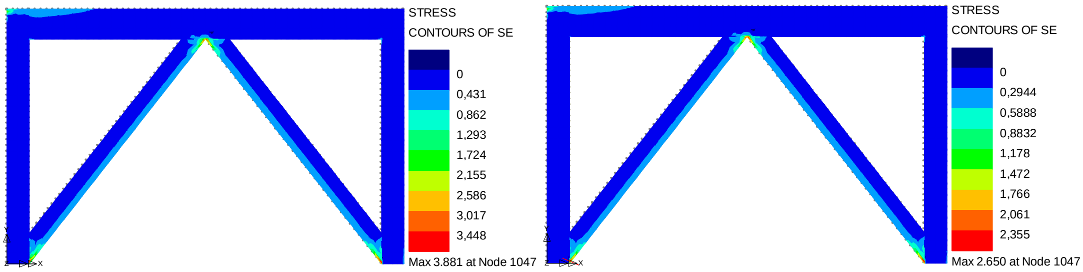
(a) Maximum equivalent stresses (b) Occurring initial crack and stresses

Fig. 7 Maximum equivalent stresses and occurring initial cracks in the frame-3



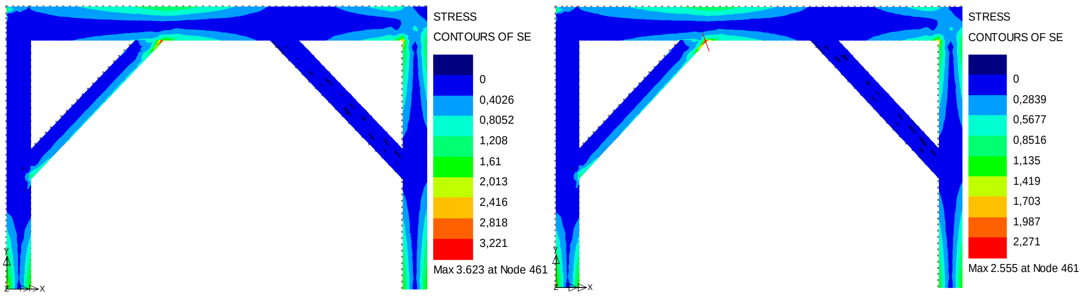
(a) Maximum equivalent stresses (b) Occurring initial crack and stresses

Fig. 8 Maximum equivalent stresses and occurring initial cracks in the frame-4



(a) Maximum equivalent stresses (b) Occurring initial crack and stresses

Fig. 9 Maximum equivalent stresses and occurring initial cracks in the frame-5



(a) Maximum equivalent stresses (b) Occurring initial crack and stresses

Fig. 10 Maximum equivalent stresses and occurring initial cracks in the frame-6

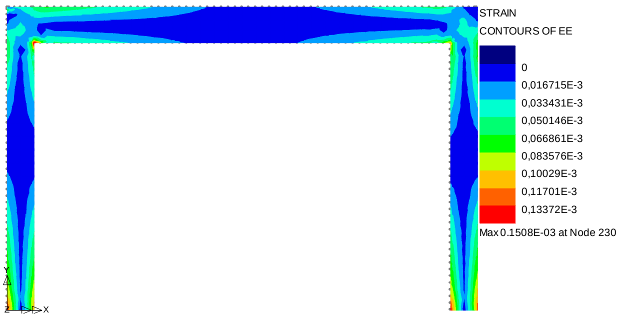


Fig. 11 Maximum equivalent strain contours of frame 1

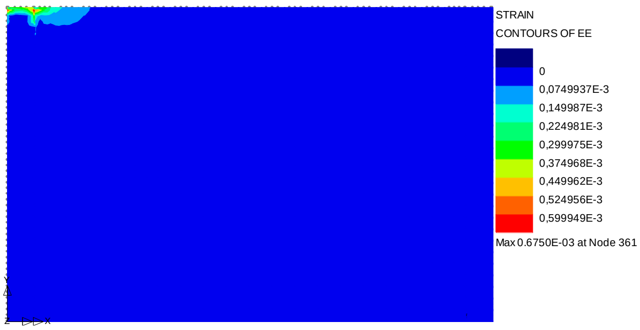


Fig. 12 Maximum equivalent strain contours of frame 2

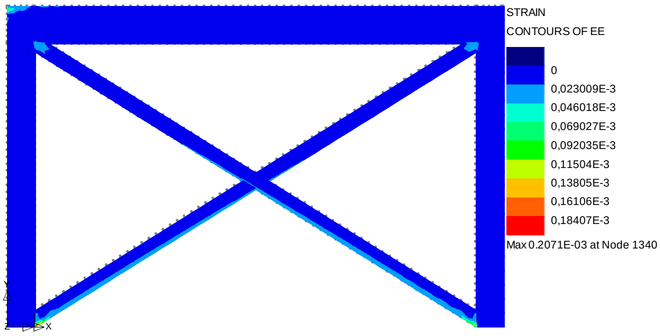


Fig. 13 Maximum equivalent strain contours of frame 3

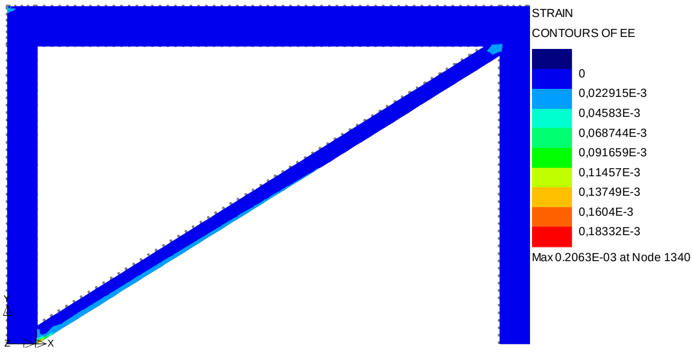


Fig. 14 Maximum equivalent strain contours of frame 4

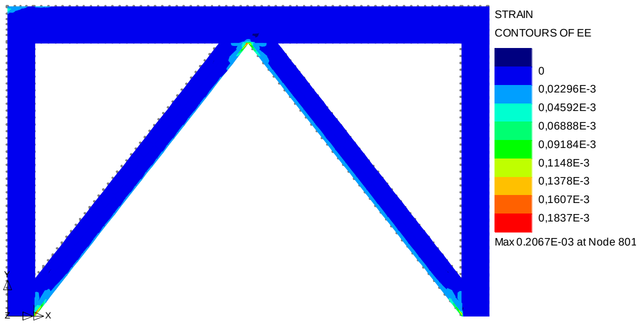


Fig. 15 Maximum equivalent strain contours of frame 5

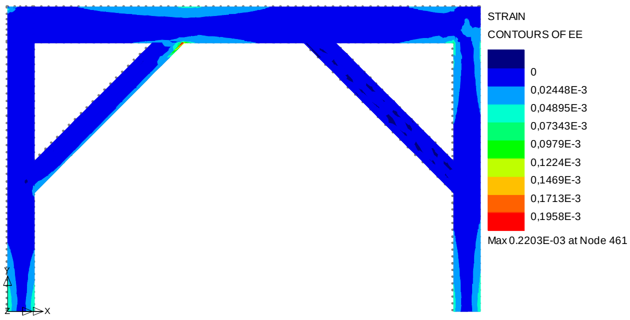


Fig. 16 Maximum equivalent strain contours of frame 6

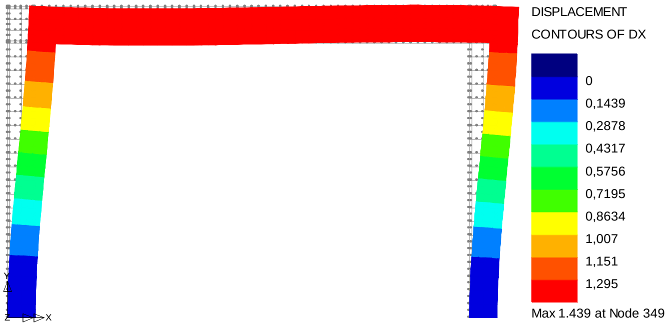


Fig. 17 Maximum horizontal displacement contours of frame-1

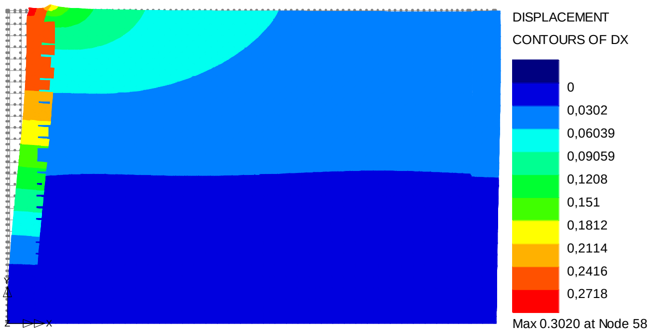


Fig. 18 Maximum horizontal displacement contours of frame-2

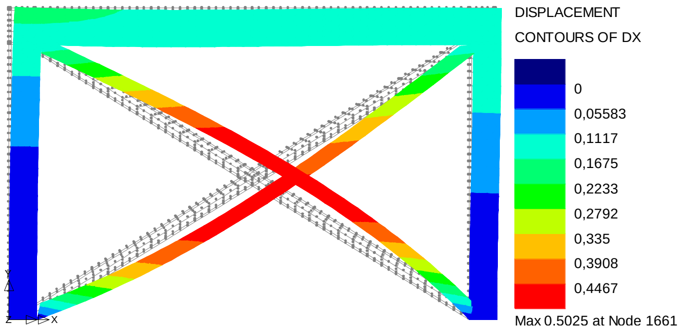


Fig. 19 Maximum horizontal displacement contours of frame-3

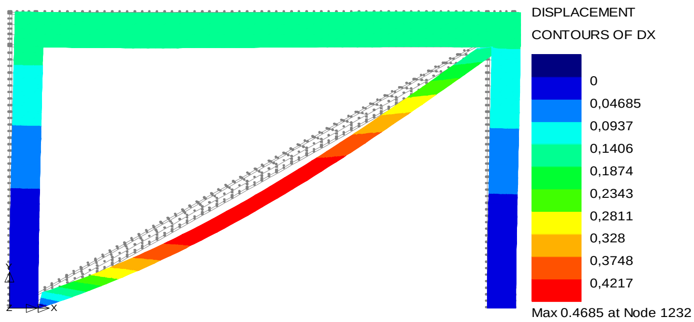


Fig. 20 Maximum horizontal displacement contours of frame-4

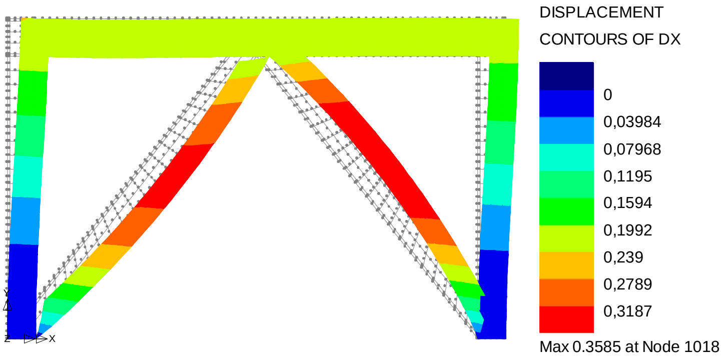


Fig. 21 Maximum horizontal displacement contours of frame-5

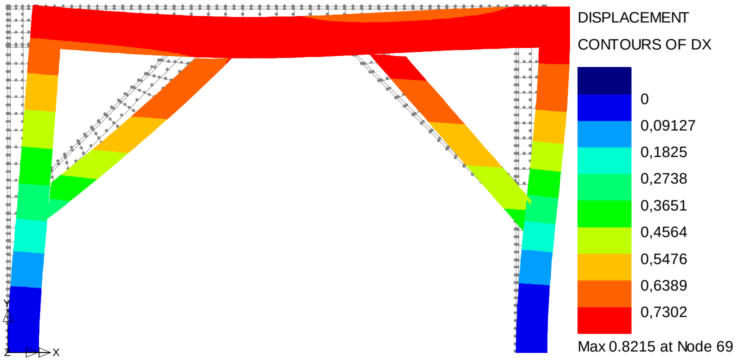


Fig. 22 Maximum horizontal displacement contours of frame-6

obtained from frame-3 are smaller than the ones obtained from other the frames having different stiffening members. This means that the frame 3 is very well behaved.

Variations with horizontal loading of equivalent stresses at the 587 node point which is maximum of stress value for the frame-1 are given in Fig. 24. As seen from this figure, as horizontal load in all models taken into account in this study increases, the equivalent stresses at the 587 node-point increase. Also, it is seen that equivalent stress values obtained from frame-2 are smaller than the ones obtained from other models. On the other hand, the added stiffener members are seen to be beneficial on the performance of basic structural elements such as beams-columns. This finding reveals that the frames having different stiffening members are safer than frame-1. Also, equivalent stresses values obtained from frame-3 are smaller than the other frames having different stiffening members. This means that the diagonal elements in frame 3 reduce the stresses of basic structural elements such as beams and columns.

Variations with horizontal loading of equivalent strains at the 203 node point which has maximum of strains value for the frame-1 are given in Fig. 25. From this figure, equivalent strain values obtained from frame-2 are smaller than the ones obtained from other models. Also, as horizontal load in all models taken into account in this study increases, the equivalent strains at the 203 node-point increase. On the other hand, the equivalent strains of the frames having different stiffening members are seen reducing. In other words, the added stiffener members are seen to be benefit on behaviour of basic structural elements such as beams-columns. This finding reveals that frame-1 is unsafe according to the other models. On the other hand, equivalent strains values

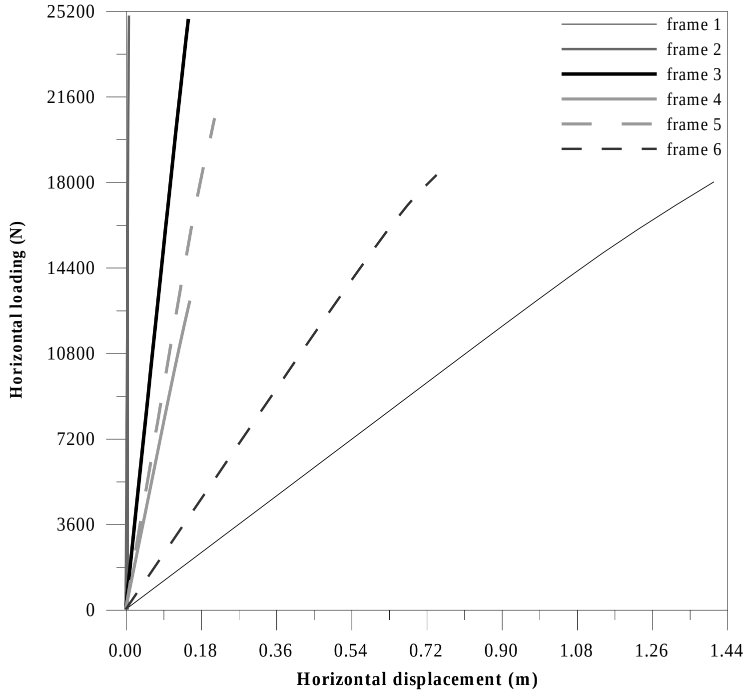


Fig. 23 Variation with horizontal loading of horizontal displacements at the 716 node point

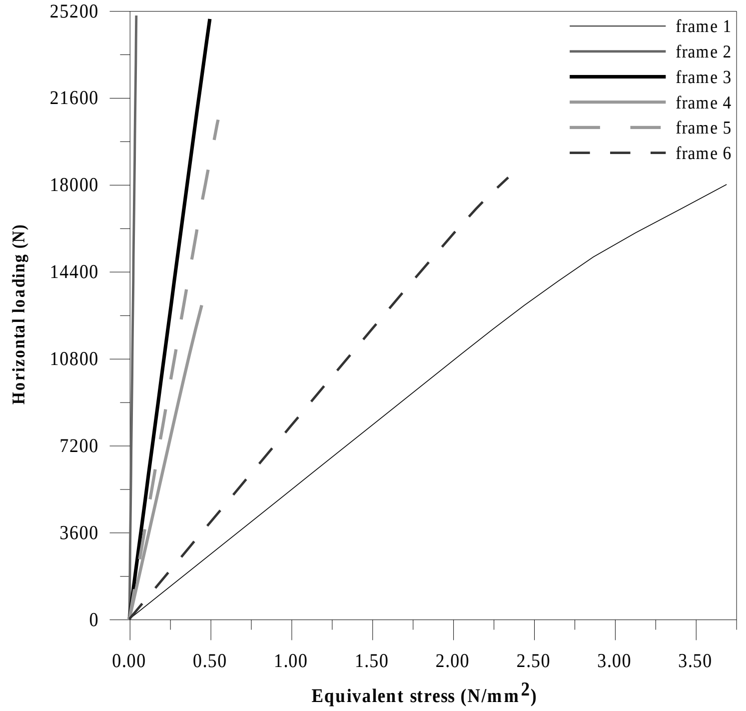


Fig. 24 Variation with horizontal loading of stresses at the 587 node point

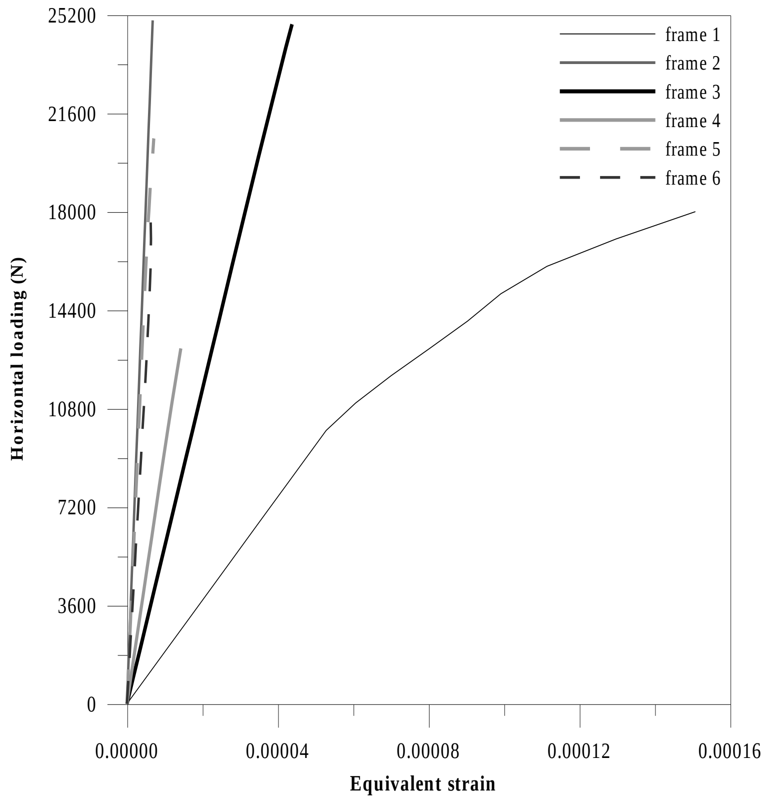


Fig. 25 Variation with horizontal loading of strains at the 203 node point

obtained from frame-3 are smaller than the considered other frames having different stiffening members. This means that the diagonal elements in frame 3 reduce equivalent strains of basic structural elements such as beams and columns and the frame 3 is very well behaved.

The maximum stress contours and occurring cracks obtained from performed analyses of the frames are given in Fig. 26. As seen from these figures, different maximum stress values for frames having diverse stiffening members were obtained. Also, as distinct from other frames, the maximum stress values in the frame 3 and 4 occur in diagonal elements. This finding reveals that these frames are better than the other frames. Because, the diagonal elements reduce the damage in basic structural elements such as beams and columns. In addition to these, it is seen that the occurring cracks in the frame 3 and 4 not occur in the basic structural elements such as beams and columns. In other words, damages in the main structural system by sacrificing the diagonal elements are prevented. This finding reveals that, the frame 3 and 4 are very well behaved. On the other hand, maximum stress values obtained from frame 2 are greater than the other frames. This means that the frame-2 behaves in a rigid manner. But, occurring cracks in the frame-2 occur in the basic structural elements such as beams and columns. But nonetheless, maximum stress values and occurring cracks obtained from frame 2 not occur in the basic structural elements such as beams and columns. This finding demonstrates that the frame-3 is very well performance. Therefore, frame-3 can be used as an alternative to shear walls.

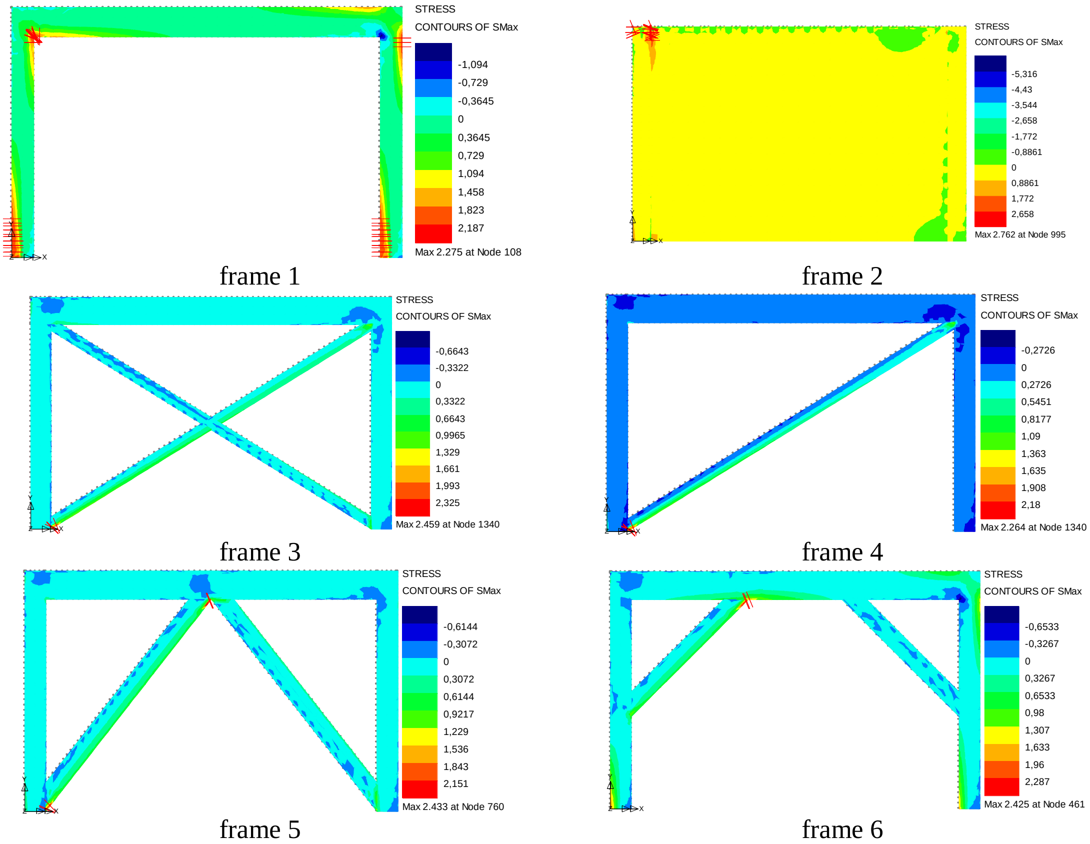


Fig. 26 Maximum stresses and occurring cracks in the considered frames

4. Conclusion

The purpose of this study is to investigate the nonlinear behavior of frames stiffened with different bracing members and shear wall under a horizontal load and to compare the obtained results with each other and with moment-resisting frame (frame-1). These comparisons are made separately for the horizontal loading, equivalent stresses, equivalent strains and horizontal displacements for the frames considered in this study. The main conclusions and recommendations drawn from this study are given below:

- The maximum stress and maximum strain values in the frames having different stiffening members as distinct from frame-1 and frame-2 occur in the diagonal elements. This finding reveals that diagonal members get prevented from the damages the main structural system by sacrificing themselves. In other words, the diagonal elements reduce damage in basic structural elements such as beams and columns.
- The initial cracks occurring in the frames having different stiffening members take place in the diagonal elements. From this point of view, frames having different stiffening members are more suitable to horizontal loads such as earthquake loads.
- Maximum horizontal displacement value obtained from frame-1 is greater than the other frames. Also, maximum horizontal displacement values obtained from other frames, except

frame 3, frame 4 and frame 5, occur at top node points. This result reveals that there is not a contribution to the performance of basic structural elements such as beams-columns of the additional stiffness members in the frame 2 and frame 6.

- The maximum horizontal displacement values obtained from frame 3, frame 4 and frame 5 as distinct from the other frames occur in the diagonal elements. This finding demonstrates a reduction at the top node points' displacement values by creating too many load paths.
- Equivalent stresses, equivalent strains and horizontal displacements in all the models increase by horizontal loading.
- Frame-1 in terms of equivalent stresses, equivalent strains, load factor and horizontal displacement values is unsafe according to other models in this study.
- These results show that the selection of right stiffness members in the design of reinforced concrete buildings under horizontal loads is vitally important in terms of safety.
- Results of this research reveal that the strength and energy absorption capability of stiffened frame models increase significantly in comparison to frame 1.
- The performed analyses demonstrate that frame 3 shows the better performance and these stiffened frames with the x-shaped diagonal elements can be an alternative to shear walls. In other words, frame 3 is far more suitable for design in terms of safety and economics for horizontal loads.

Acknowledgments

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