PAPER • OPEN ACCESS

Influence of Joint Connection Modelling on Dynamic Characteristic of the Buildings

View the article online for updates and enhancements.

Influence of Joint Connection Modelling on Dynamic Characteristic of the Buildings

Ahmet Tugrul Akyildiz [1], Alicja Kowalska-Koczwara [1], Arkadiusz Kwiecien [1]

[1] Cracow University of Technology, Warszawska 24 St., 31-155 Cracow, Poland

tugrulakyildiz@gmail.com

Abstract. In this paper, a 6 storey existing RC building is investigated in terms of having different joint types between the masonry infills and RC frame. First, the building is modelled according to the pre-described project of its own. Then, dynamic characteristics of the structure are found for the bare frame, since it is the most common type of designing technique being used currently. Following that, different connection approaches are implemented along the infill-frame interfaces of the building elements. In order to understand influence of the joints on the building dynamic characteristics, two extreme conditions are taken into consideration, namely stiff and hinged connections. Furthermore, an innovative solution using flexible polyurethanes (polymer PM) as a joint element between RC frame and masonry infill is proposed. This new method exhibits a highly ductile behaviour and therefore it increases the modal periods of the building, compared to the stiff one. On the other hand, due to the intrinsic features of the material such as visco-elastic behaviour that leads to dissipate energy, a visible contribution to the building damping parameters is also observed in time history analysis. Finally, three different connection options are compared between each other and the results are discussed. Large deformability capacity with highly durable reaction ability against the external forces is one of the most crucial points from structural engineering perspective. According to the results of this study, the new proposed method gives promising expectations that such approach might be used in seismic areas both for existing buildings and new constructions. In addition, dynamic behaviours of the building with different joint types also revealed the importance of masonry modelling whilst designing as well as choosing an appropriate connection method.

1. Introduction

Infill masonry is currently the most widely used method in RC buildings for the purposes of participation, insulation, decoration etc. In spite of its popularity, structural engineering still has major concerns regarding behaviour of the infills under seismic loads. In most instances, infill walls are considered only by their weights during the design process of the buildings, thus their effects on the dynamic properties of the structures are either neglected or partially considered with some approximate approaches.

In order to comprehend better the effects of infill-frame interaction on the dynamic characteristics of buildings, understanding of structural dynamics is required. First step for better understanding the structural behaviour is to define its dynamic characteristics. Dynamic characteristics of structures are independent from external excitation and they consist of natural frequencies, mode shapes and damping ratios.

Dynamic motion equation for the structural systems (with mass m, stiffness k and damping c) excited kinematically is defined by equation (1);

$$m\ddot{u} + c\dot{u} + ku = -m\ddot{u}_g \tag{1}$$

The term $\ddot{u}_g$ is the ground acceleration, thus $-m\ddot{u}_g$ indicates the earthquake loading. Similarly, $m\ddot{u}$, $c\dot{u}$ and ku correspond to the inertial, damping and elastic forces, respectively [1]. Deriving from the equation (1) it can be found that natural frequency f (inverse of natural period T) of a structure is related to mass and stiffness factors, according to equation (2).

$$f = \frac{1}{T} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{2}$$

In other words, natural frequency is the number of times a building oscillates back and forth (completing one cycle) and it depends on intrinsic features of the building that are stiffness and mass. On the other hand, every building has specific ways of vibrating naturally characterized by mode shapes, related to the different characteristic distorted shapes of the deformed buildings and to the particular frequencies. Earthquake excitations cause dynamic loads on the structures in the form of inertial forces and thus additional motions with the natural frequencies and the related modes might occur. In the excited building, oscillation level increases when damping is low, causing displacements possibly larger than the building capacity and its failure as a consequence. Damping of structures can be defined as ability of dissipating energy during the dynamic response and should be recognized well for each building analysed dynamically. Basic factors affecting damping are material of construction, structural configurations and environmental effects such as water and air surrounding buildings, however this influence is ignored in most instances.

Damping of the buildings can be increased in several ways. Among modification of the basic factors, supplemental ones are increasing their efficiency in reducing vibrations, such as energy dissipation devices using hysteretic, friction and viscous methods. However, in accordance with the purpose of this paper, here will be focused on the inherent damping features of structures. Particularly, cracks that occur in structural and non-structural elements as well as inelastic deformations lead to this type of damping [2]. Determining of certain damping values for the buildings is very challenging at the present time, due to complexity of the problem. Unlike stiffness and mass, damping cannot be characterized by just geometry and material properties, but many experiments are also needed [3-4]. However, some common approximate damping ratios for the buildings exist in the literature, determined on the basis of material types. Damping ratios for the civil structures are generally considered relatively low, in a range between 0.1 to 5.0% [1, 4-7].

In this study, an RC building that is designed according to current Turkish Seismic Code (TSC) [8] is investigated in terms of aforementioned features, namely natural period and mode shapes. The damping ratio of 5.0% [5, 9] is chosen for the tested structures, because it is one of the most widely used values for damping ratios of RC buildings. Bare frame is first performed, due to being the general design approach. Furthermore, stiff and hinged connections between the infills and RC frame buildings are tested in order to understand discrepancy of two extreme modelling techniques. A new proposed method using Polymer Flexible Joints (PFJ) is also created [10-13] and all of the results of different models are compared.

2. Modelling of joints in FEM programme

Modelling masonry infills in buildings is a matter of interest for decades [14]. Especially their contribution on the dynamic behaviours of structures is the underlying reason. Researchers focusing on behaviour of masonry structures are particularly interested in two different modelling techniques: macro and micro models. The macro model is a simplified and approximate approach using equivalent strut patterns, to simulate lateral load bearing features of the masonries. The micro model is very detail

oriented and relatively more accurate, having thus some drawbacks such as complexity and larger time consuming calculations. Majority of studies in literature focus on behaviour of masonry itself, using either aforementioned models, while aiming to understand influence of them on building overall dynamic characteristics. Therefore, primary purpose is investigating the masonry infills detailed via considering their nonlinear tendencies under cyclic loads. However, within the scope of this paper infill walls are considered with their linear material properties, since it is aimed to investigate different joint types and their influences on building features, rather than investigating the masonries.

All of the column and beam members are modelled as one-dimensional bars in the structural system, where shear walls and masonries are designed with two dimensional shell elements. Both in-plane and out-of-plane features are used for the shells, for this reason they are also preferred for joint modelling as interface elements presented in figure 1 [15]. Three different connection types are considered for the joints between RC elements and infill walls. Stiff connection represents a rigid joint structure between the interfaces of masonry and frames. For this type of tie, continuous bonding is tough along the surfaces and masonry-to-frame connection. It is provided by a direct contact without any interface element, see figure 2. On the contrary, the hinged connection is modelled to represent a connection loss phase. Stiffness parameters along the bonding zone are decreased adequately, thus neither force nor moment transfer is actualised, see figure 2. Aiming to make a comparison between these two extreme conditions, a polymer based new material polyurethane PM (developed previously [10-13]) is implemented as an interface element. It has high deformability features together with the high resistance capability against dynamic loads, what allows them to dissipate energy via ductile manner. Material properties are taken from previous studies [12-13, 16] and they are listed in table 1, where E_{pm} is Young's modulus, ν is Poisson ratio, ε is ultimate strain (50÷150 % depending on the rate of load application) and ξ is material damping ratio. These flexible joints are designed with shell elements having 20 mm thickness in entire masonry-to-frame connections. In a similar way of stiff and hinged types, polyurethane PM joints are also implemented along the all peripheral lengths of the masonries as shown in figure 2.
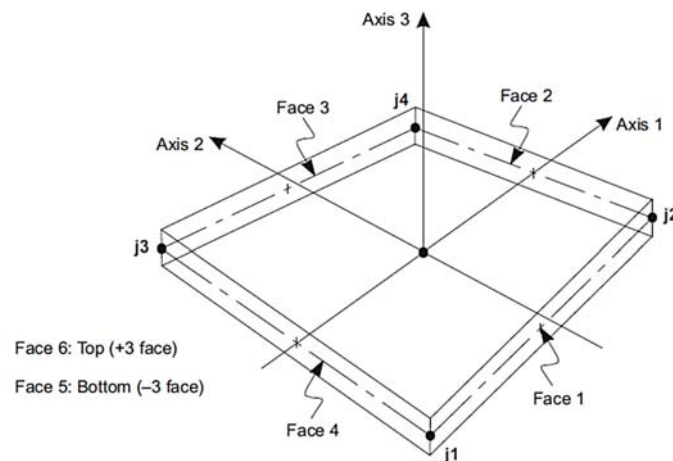

Figure 1. Four-node quadrilateral shell element [15]

Table 1. Material properties of the polyurethane PM

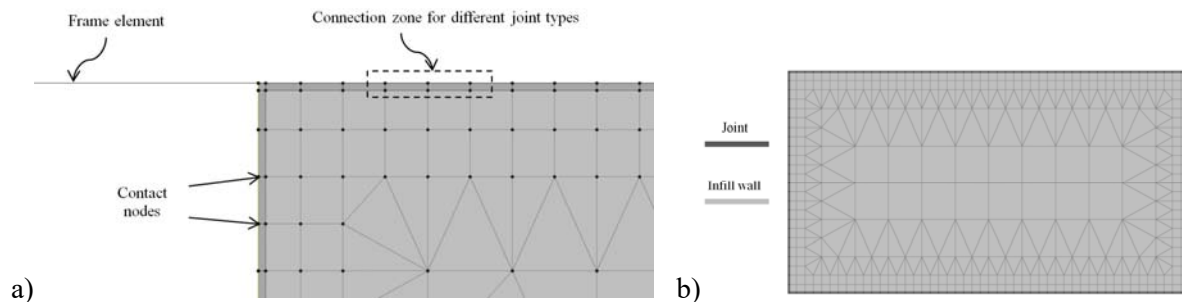| E_{pm} (Mpa)	ν	ε	ξ
4.5	0.47	0.5 - 1.5	0.06

Figure 2. a) Infill-frame joint detail and b) joint implementation layout

3. Description of the analysed building

The analysed building is located in Istanbul province of Turkey. It has 6 storeys above the ground and it is designed for residential purposes. One-way ribbed slabs are used for the floors. These are combined with the beams that are connected to the vertical elements, columns and shear walls. Minor changes existing in different storeys are neglected, thus an identical floor layout is created for all different levels. Structural system is connected to the ground by fixed restraints. Typical floor plan and 3D numerical model of the building is shown in figure 3.
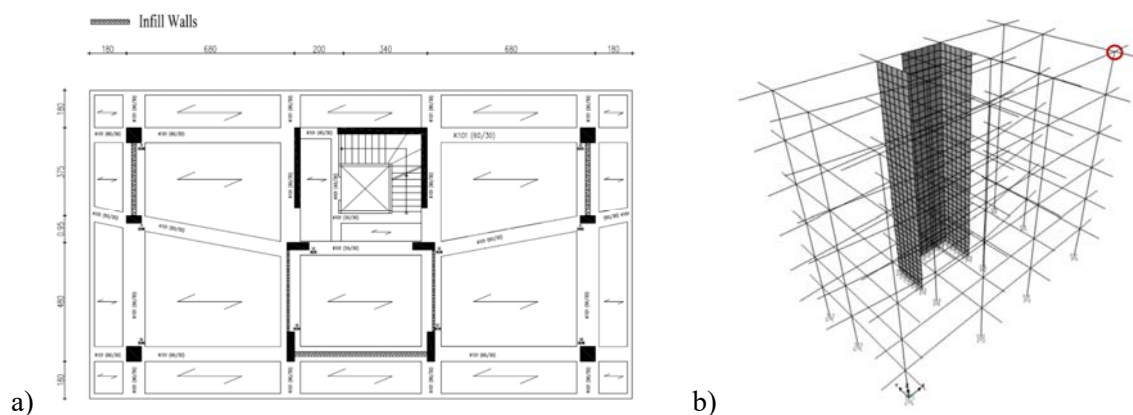

Figure 3. a) Typical floor plan and b) 3D numerical model

Structural system was not calculated considering the stiffness influence of infill walls during the design process. Therefore, this original form of the model is called as bare-frame, though shear walls exist. The other models with the masonries are labelled based on the joint types, i.e. stiff, hinged and flexible (polyurethane PM). Since structural plans do not comprise the infill walls, an arbitrary mass distribution of them is made while creating numerical models, without stiffness influence, see figure 3. The masonries are assumed to be hollow-clay bricks and two different thickness values are used, for external walls 19 cm and for the internal ones 10 cm. Their mechanical properties are determined based on FEMA-273 regulations assuming masonries are in fair condition [17], which have compressive strength f_{me}=4 MPa and Young's modulus E_{me}= 2200 MPa. Besides, all of the concrete members have strength class C35/45 with Young's modulus 33000 MPa and Poisson ratio 0.20 [18].

4. Dynamic characteristics of the analysed building

Building dynamic properties are investigated in two different phases. First, natural vibration frequencies are found with corresponding mode shapes. This is a fast and effective method for understanding the general structural response against dynamic motions. According to the results, stiff connection type of building has the highest frequencies. On the other hand, hinged connection exhibits the same results of the bare one due to the lack of joint strength. Flexible joint results indicate relatively stiff behaviour in comparison to the hinged one, whereas a more ductile behaviour is observed against to the stiff connection, since frequencies are found among these two reference joint models. Frequencies are given in table 2 for two major axis X and Y, together with the corresponding modal participation mass ratios. Illustrations of the deformed shapes for the 1st modes are also provided in figure 4.

Table 2. Building modal properties for the different joint types

Mode	Bare-Frame			Stiff Joint			PM Flexible Joint		
	Frequency (Hz)	Mass Participation (X dir.)	Mass Participation (Y dir.)	Frequency (Hz)	Mass Participation (X dir.)	Mass Participation (Y dir.)	Frequency (Hz)	Mass Participation (X dir.)	Mass Participation (Y dir.)
1	0.859	0.35	0.00	1.638	0.68	0.05	1.127	0.43	0.00
2	1.298	0.13	0.45	1.885	0.00	0.14	1.464	0.12	0.38
3	1.812	0.23	0.25	2.263	0.05	0.53	1.925	0.17	0.33
4	3.077	0.07	0.00	5.634	0.09	0.00	3.787	0.06	0.00
5	5.503	0.04	0.11	6.139	0.00	0.01	5.777	0.03	0.09
6	6.177	0.00	0.00	6.789	0.02	0.04	6.229	0.01	0.01

a) 1st mode: 0.859 Hz   b) 1st mode: 1.638 Hz   c) 1st mode: 1.127 Hz
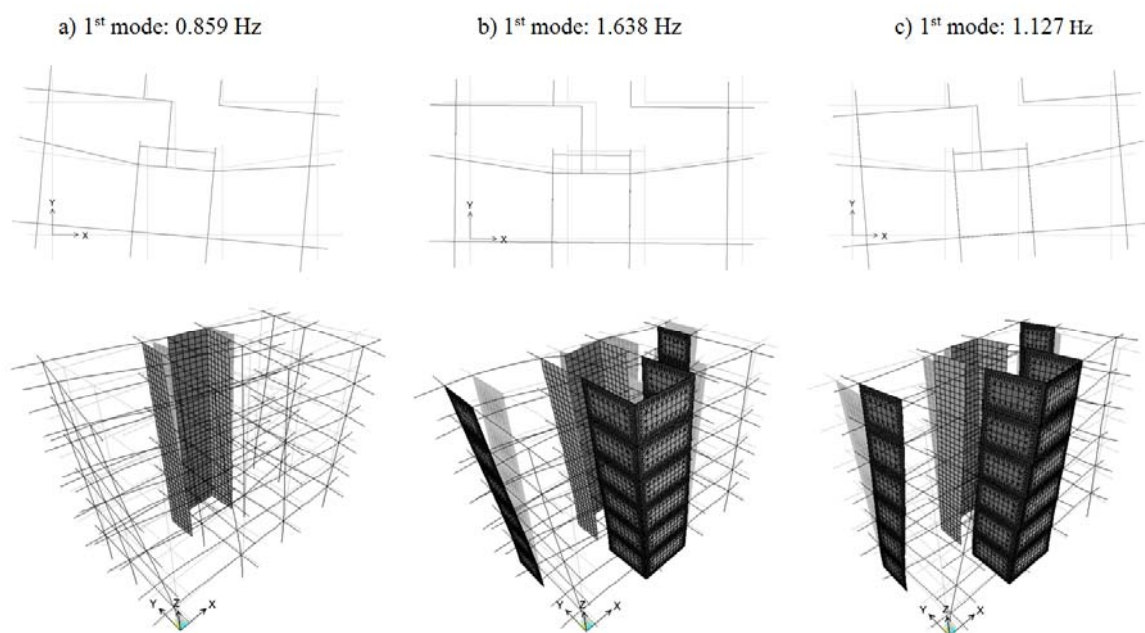

Figure 4. Natural mode frequencies with plan and 3D views:
a) bare-frame, b) stiff joint, c) PM flexible joint

In order to understand the dynamic behaviours with further details, more exhaustive analyses are performed using Time History Analysis method. Three different seismic records are used. Their names and peak ground accelerations (PGA) with some other information are given in table 3.

Table 3. Seismic records details

Earthquake Name	Date	Depth (km)	Magnitude (M_w)	PGA (g)	Record Time (sec)
Duzce	12.11.1999	10	7.2	0.42	26
El Centro	18.05.1940	16	6.9	0.32	12
Erzincan	13.03.1992	23	6.3	0.43	28

Dynamic excitation results are compared for two different cases, which are displacement and acceleration. A reference point is chosen on the top floor of building for performing the comparison, it is shown with a red circle in figure 3. Additionally, to the time domain acceleration graphs, Fast Fourier Transform (FFT) process is also done and the results are given together with time-displacement and time-acceleration values in figure 5 and figure 6 for X and Y directions, respectively. Maximum values of the graphs are given too, see table 4.
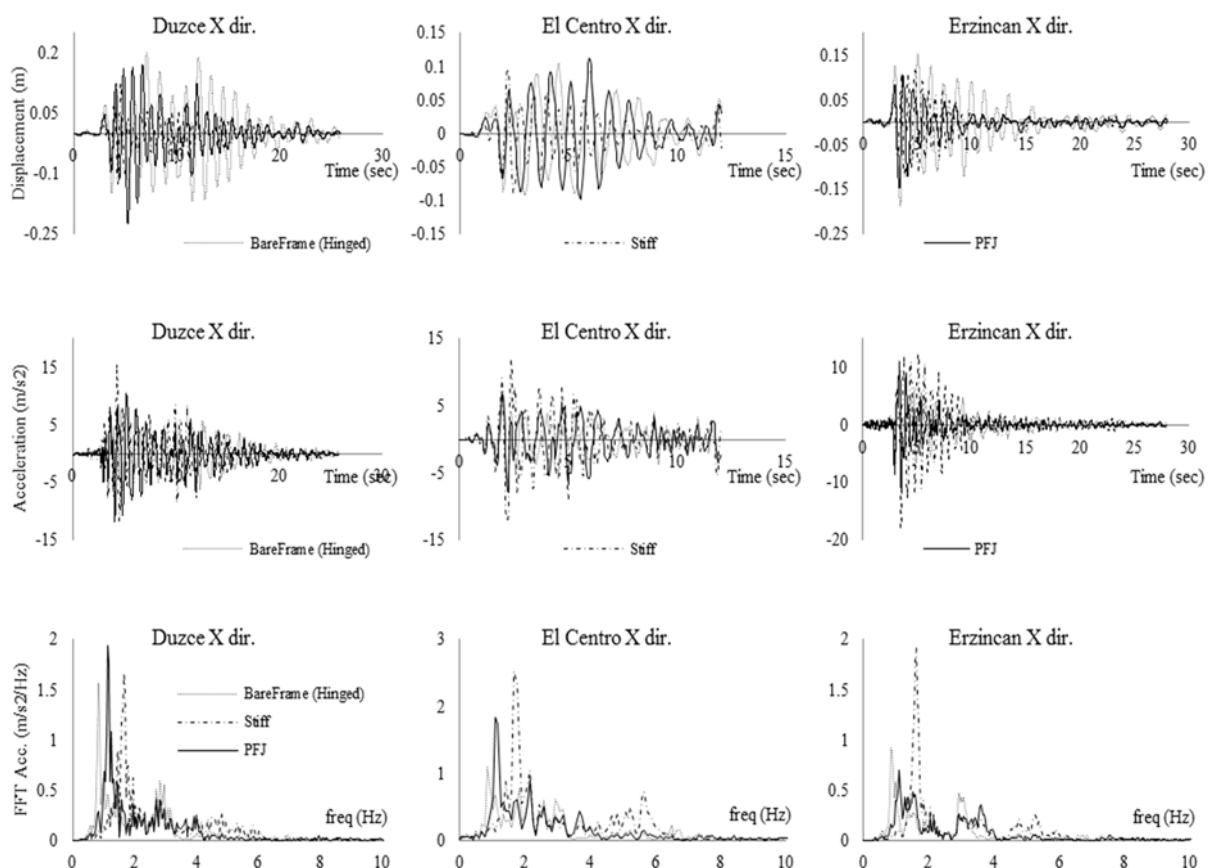

Figure 5. Displacement, acceleration and FFT (acceleration) results for the reference point in X direction
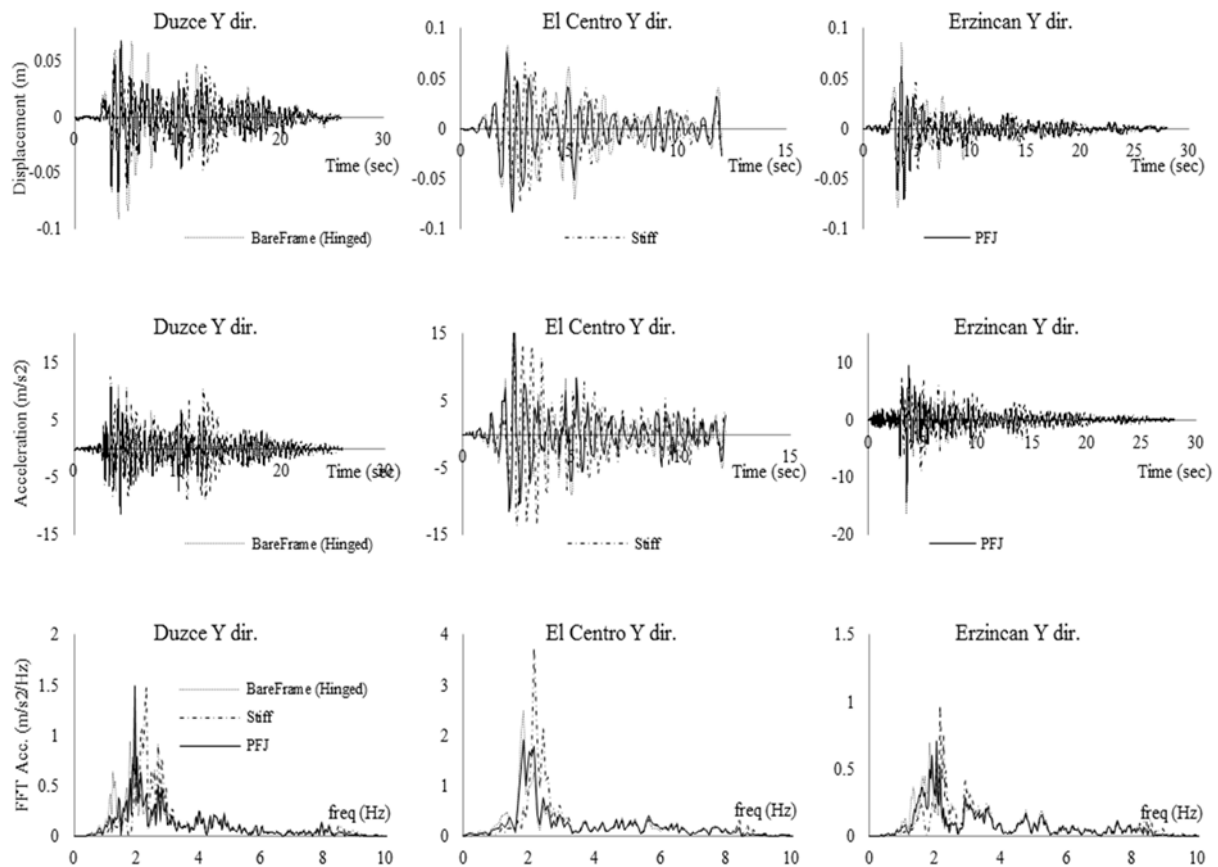
Figure 6. Displacement, acceleration and FFT (acceleration) results
for the reference point in Y direction

According to the results obtained, stiff joint type tends to show the highest resistance in terms of displacement, where bare-frame (or hinged type, since their results are identical) exhibits relatively more ductile behaviour compared to the stiff and flexible joint buildings. In the other comparison, acquired acceleration data gives a sign that stiff type of connection leads the building to be exposed to higher acceleration demands, whereas hinged and flexible joint exhibit similar outcomes and less acceleration values, resulting in lower inertial forces acting on the structures.

Table 4. Comparative results of the maximum values for the reference point

		Bare-Frame		Stiff Joint		PM Flexible Joint	
	THA Record	X dir.	Y dir.	X dir.	Y dir.	X dir.	Y dir.
Displacement (cm)	Duzce	20.1	9.1	12.8	6.3	22.5	6.9
	El Centro	10.5	8.2	9.8	7.2	11.2	8.3
	Erzincan	18.5	8.5	12.5	4.6	14.6	7.1
Acceleration (m/s^2)	Duzce	10.37	10.91	15.45	12.53	11.74	11.49
	El Centro	7.18	13.43	12.27	15.10	7.84	15.86
	Erzincan	10.66	16.34	18.20	9.28	11.25	14.35
Peak FFT (m/s^2/Hz) - Corresponding Freq. (Hz)	Duzce	1.57 - 0.81	0.95 - 1.93	1.67 - 1.62	1.49 - 2.32	1.93 - 1.12	1.49 - 1.93
	El Centro	1.10 - 0.83	2.49 - 1.83	2.52 - 1.66	3.75 - 2.16	1.84 - 1.08	1.91 - 1.83
	Erzincan	0.92 - 0.82	0.70 - 1.82	1.91 - 1.61	0.98 - 2.15	0.70 - 1.07	0.71 - 2.04

5. Discussion and conclusion

In this paper, a building in a high risky seismic zone is investigated in terms of dynamic characteristics. Ductility and strength are two of the most crucial issues, which buildings must provide against seismic loads from the perspective of dynamic characteristics. A polymer based new material for, being used in modelling as a bonding element between infill masonry and RC frame is tested within this context. The results are compared for modal analyses and dynamic excitations. These are listed as below:

- Usage of infill walls drastically changes the building natural frequencies. However, masonries are considered as linear members and their non-linear after-crack behaviours are not taken into account in this study. Despite this simplification, it can be still seen the importance of infills on building dynamic characteristics. Moreover, polyurethane PM joints in the building exhibit relatively ductile behaviour compared to the stiff type of joints. This is an expected result since the new proposed material has significantly lower Young's modulus value than the masonry walls have.

- Time History Analyses reveal similar results, where flexible joints exhibit less stiffness rate as against to the stiff type of connection that can be seen from the displacement based graphs. On the other hand, in the frequency and time domain acceleration graphs, hinged joints and flexible joints have quite similar values though discrepancy between them is remarkable in the displacement based outcomes. Damping properties of the polyurethane PM can be one of the underlying reasons for this.

- Different seismic records give similar frequency results for the different connection types internally. In other words, each connection type responded similarly to the different excitations in terms of frequencies according to the FFT results. However, peak values of the FFT accelerations have larger variety relatively, in which stiff joint has the highest values and bare-frame has the lowest.

- According to the results obtained, usage of the flexible joints can be preferred for interfacing element between masonries and RC frames. Besides, although de-bonding issue is not considered for the numerical analyses, previous studies [10-13] give promising results regarding this case. Due to its large deformability capacity together with the high bonding strength, the polyurethane PM based flexible joint material can be used for dissipating energy in case of dynamic loads forcing. This is a crucial point especially for the buildings without reinforced masonries, since in Turkey most of the buildings are untied to the frames and a strong bonding is needed in order to mitigate seismic hazard on the structures [19].

References

[1]   A. S. Elnashai & L. Di Sarno, "Fundamentals of Earthquake Engineering", *Chippenham, Wilts: John Wiley & Sons*, 2008.

[2]   Z. Celep, "Yapı Dinamiği", *Istanbul, Turkey: Beta Dağıtım*, 2011, (in Turkish).

[3]   A. K. Chopra, "Dynamics of Structures: Theory and Applications to Earthquake Engineering", *Englewood Cliffs, New Jersey: Prentice Hall*, 1995.

[4]   R. W. Clough & J. Penzien, "Dynamics of Structures", *Berkeley, CA.: Computers & Structures Inc.*, 2003.

[5]   D. Bernal, M. Döhler, S.M. Kojidi, K. Kwan, Y. Liu, "First Mode Damping Ratios for Buildings", *Earthquake Spectra*, vol. 31, pp. 367–381, 2015.

[6]   H. Bachmann, J.W. Amman, F. Deischl, J. Eisenmann, I. Floeghl, G.H. Hirsch, G.K. Klein, G.J. Lande, O. Mahrenholtz, H.G. Natke, H. Nussbaumer, A.J. Pretlove, J.H. Rainer, E. Saemann, L. Steinbeisser, "Vibration Problems in Structures", *Zurich: Birkhäuser*, 1995.

[7]   J.D. Stevenson, "Structural Damping Values as a Function of Dynamic Response Stress and Deformation Levels", *Nuclear Engineering and Design*, vol. 60, pp. 211–237, 1980.

[8]   Ministry of Public Works and Settlement, "Turkish Seismic Code", *Government of Republic of Turkey*, 2007.

[9]   P. Khajeh Hesameddin, A. Irfanoglu, T.J. Hacker, "Effective Viscous Damping Ratio in Seismic Response of Reinforced Concrete Structures", *11th International Workshop on Advanced Smart Materials and Smart Structures Technology. United States: University of Illinois, Urbana-Champaign*, 2015.

[10] A. Kwiecień, "Polymer flexible joints in masonry and concrete structures", *Monography No. 414, Wyd. Politechniki Krakowskiej, Seria Inżynieria Lądowa, Kraków*, 2012, (in Polish).

[11] P. Kisiel, "The stiffness and bearing capacity of Polymer Flexible Joint under shear load", *Procedia Engineering*, vol. 108, pp. 496–503, 2015.

[12] A. Kwiecień, M. Gams, T. Rousakis, A. Viskovic, J. Korelc, "Validation of a New Hyperviscoelastic Model for Deformable Polymers Used for Joints between RC Frames and Masonry Infills", *Engineering Transactions*, vol. 65(1), pp. 113–121, 2017.

[13] A. Kwiecień, M. Gams, A. Viskovic, P. Kisiel, J. Korelc, T. Rousakis, "Use of polymer flexible joint between RC frames and masonry infills for improved seismic performance", *SMAR'2017, ZURICH (13-15.09.2017). http://www.smar-conferences.org/smar/SMAR_2017_Proceedings/papers/179.pdf*, 2017.

[14] F.D. Trapani, G. Macaluso, L. Cavaleri, M. Papia, "Masonry infills and RC frames interaction: literature overview and state of the art of macromodeling approach", *European Journal of Environmental and Civil Engineering*, vol. 19, pp. 1059-1095, 2015.

[15] "CSI Analysis Reference Manual", *Berkeley, CA.: Computers & Structures Inc.*, 2005.

[16] A. Kwiecień, B. Zając, R. Jankowski, "Static and dynamic properties of a flexible joint working in cracked historical masonries", *Proceedings of the VI International Conference on Structural Analysis of Historic Construction, SAHC08, 2-4 July 2008, Bath, United Kingdom*, pp. 931–939, 2008.

[17] Federal Emergency Management Agency, "NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA Publication 273)", *Washington D.C.*, 1997.

[18] Turkish Standards Institute, "TS-500 Building Code Requirements for Reinforced Concrete", *Ankara, Turkey*, 2000, (in Turkish).

[19] H. Sezen, A.S. Whittaker, K.J. Elwood, K.M. Mosalam, "Performance of reinforced concrete buildings during the August 17, 1999 Kocaeli, Turkey earthquake, and seismic design and construction practise in Turkey", *Engineering Structures*, vol. 25, pp. 103–114, 2003.