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Seismic Response of Anchorage Elements Used in Curtain Wall Systems

Ferhat PAKDAMAR[*1], Özgün BOZKURT[2]

Abstract

Utilizing curtain wall systems as outer covering of a building has been enormously increasing for the last years. Past earthquakes have revealed the wrong design of curtain wall systems connections that can seriously endangers human life. In this study, design procedures proposed by different international and national earthquake codes and specifications to compute the forces in the connection of curtain wall systems are summarized. As a real example, a regular 30-storey reinforced concrete building is considered, and a Finite Element Model is created for this structure. A detailed model for the building and the curtain wall systems and their connection anchors are considered. The axial and shear forces in the anchors are computed using the average results of seven sets of time history analyses. The results are compared with the results of building model using spectrum modal combination analyses and the forces in the connection anchors are proposed by different Specifications; Turkish Earthquake Code 2007, Turkish Earthquake Code 2018, Federal Emergency Management Agency, European Standard. As a result, it can be concluded that the seismic forces used for the design of anchors of the curtain wall systems are better estimated by the specification suggested by Turkish Earthquake Code 2007 compared to the detailed model results.

Keywords: curtain wall systems, seismic performance, facade, non-structural elements, anchorage

1. INTRODUCTION

In the world, developments and increase the variety of materials used in conjunction with the technology affects the use of the curtain wall system positively. Popularity of curtain wall systems especially on high rise buildings are increasing day by day because of being light weight, aesthetic and easy installation. Designing a system widely used correctly is quite important. There are two main principles to be considered in the design of curtain wall systems. First point is the seismic behavior of curtain wall systems under a strong ground motion. Second point is about

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comfort like air or water impermeability [1], wind resistance [2], solar control [3], eq. resistance [4] etc. Seismic behavior of curtain wall systems are vital when ground is shaking. Any facade parts, damaged can endanger for human life. Past earthquakes confirm this danger [5]. Additionally, wrong design or assembling of a curtain wall system parts wrongly affects welfare and comfort of building residents in a negative way [6]. Designing of curtain walls properly are very important for the reasons, explained above. Seismic loads, effecting to curtain wall system design play an important role, especially in high-rise buildings [7, 8]. However, calculation and assessments of seismic loads, acting on the facade systems has not been the subject of much research around the world there are limited study. Galli [9] compared the seismic forces acting on facade systems for various codes in his doctoral dissertation and he described the differences between them. In addition, results of some tests, acted to an actual curtain wall system like wind strength test, the water-air tightness test, etc. and computer model of this system is compared. Ting [10] mentioned two approaches about response of curtain wall systems under lateral story drifts when an earthquake happening. There are two more important studies [11, 12] about behavior of curtain walls under horizontal actions experimentally. O'Brien, et al. [13] has been formulated a closed-form equation to predict a glass panel cracking failure drift. These researches rather describes steel profiles, material tests and the history of facade systems than the effect of seismic loads. In the present study, effect of seismic loads to curtain walls, suggested in codes are compared.

2. CURTAIN WALL SYSTEMS

Curtain wall system was applied to a two story bank building in Philadelphia in 1820, for the first time in the world. There are also two representative buildings, Chicago Auditorium and Chicago Monadnock were built in 1890 and 1891 respectively. Curtain wall concept continues to improve and expand their areas with the advancement in technology. Especially, aluminum metal has substantially increased the popularity of the area with the use of facade systems [14].

Curtain wall system consists of several components. These components comprise of steel profile supporting structures, anchorage elements of steel supporting structures and covering material (glass, composite, precast, ceramic etc.). These components have to successfully pass air leakage control, vapor diffusion control, rain penetration control and condensation control tests for increasing the interior comfort of buildings. Quirouette [15] and Brenden [16] cite rules of the tests and properties of curtain wall system connections.

The most important component of a curtain wall system for the load bearing is carrier profiles. Because these steel profiles have to behave as ductile and deform harmonically with story drifts of the building on assembled under an earthquake motion. Especially with usage of aluminum in sector, curtain wall systems have become more flexible behavior and adapted the story movements. As a result they can resist to seismic forces. Building covering materials like glass, precast, ceramic, etc. are more brittle elements than load bearing steel support profiles. Expectation from these elements are air leakage control, vapor diffusion control, rain penetration control and condensation control and transfer the stress acting on them to steel profiles with seismic loads. It should be avoided from very rigid connections of the carrier steel profile to mount facade systems in the building.

3. USED REGULATIONS FOR THE CURTAIN WALL SYSTEMS

Various regulations including the design rules of the curtain wall system is available in the world. The proposed design rules in the regulations are determined in accordance with a main target. Displacements and behavior of a curtain wall system applied to a structure must not pass the life safety performance target level, while an earthquake. It has also response to internal forces occurred by seismic effects without collapsing.

Some of the regulations related to a curtain wall system with design rules are Turkish Seismic Code 2007 [17], Turkish Seismic Code 2018 [18], European Codes 8 [19], American Regulations

FEMA450 [20], Standard of New Zealand NZS1170.5 [21], Japan Regulations JASS14 [22]

3.1. Turkish Seismic Code 2007 (TDY2007) [17]

There is not a clear information about the seismic force which is effect on curtain wall system in TDY [17]. However, a seismic force description for all non-structural architectural elements and for their connection parts which connect the system to the building structure is made in the *chapter 2.11*. Because the curtain wall systems are non-structural, they are considered under the definition in the TDY2007.

In accordance with this definition, earthquake force equation for design requirements in the TDY2007 is given in Eq. (1).

$$f_e = 0.5 A_0 I w_e \left(1 + 2\frac{H_i}{H_N}\right) \quad (1)$$

This calculated earthquake load is applied to the center of gravity of the curtain wall system element in the horizantal directon to get the most unfavorable internal forces. If the element is inclined half of the force is applied vertically.

- A_0 = effective ground acceleration coefficient
- I = building importance coefficient
- w_e = weight of the component
- H_i = the height of the building on the basis of relevant element
- H_N = the total height of building which is equal to H EUROCODE-8 and h in FEMA-450.
- f_e = force which is equal to F_e in TDY2018, F_a in EUROCODE-8, F_p in FEMA-450 and F_{ph} in NZS-1170.5.
- w_e = weight which is equal to m_e in TDY2018, W_a in EUROCODE-8, W_p in FEMA-450 and W_p in NZS-1170.5.

3.2. Turkish Seismic Code 2018 (TDY2018) [18]

Earthquake force, F_{ie} which is applied to anchorage parts of curtain wall systems in Turkish Seismic Code [18] is accepted as to non structural components like Turkish Seismic Code [17]. In this context, the earthquake force which is described in *Chapter 6.2* in the code is given in Eq. (2).

$$F_{ie} = (m_e A_{ie} B_e)/R_e \quad (2)$$

m_e is the mass of element, A_{ie} is the peak ground acceleration effecting the element, B_e is amplification factor, R_e is the component behaviour factor in Eq. (2) Tables are available in the code.

3.3. European Codes EUROCODE–8 (EC8) [19]

EUROCODE is the regulation that Europian countries use. Earthquake force which is applied to curtain wall systems in EUROCODE-8 is diveded to two parts. First is anchorage forces of curtain wall system and the other is the force applied to facade system. Mentioned seismic force in Eurocode 8 [19], *Chapter 4.3.5* is given in Eq. (3).

$$F_a = (S_a \cdot W_a \cdot \gamma_a)/q_a \quad (3)$$

W_a is the weight of releavent component at i'th story for the seismic force to the i'th story. γ_a is importance factor of releavent component at i'th story. q_a is the behaviour factor of the element. There is a table for the q_a in the code. S_a is the seismic coefficient applicable to non-structural elements and the formula of it is given in Eq. (4).

$$S_a = \alpha \cdot S \cdot [3 \cdot \frac{1+z/H}{1+(1-Ta/T1)^2} - 0.5] \quad (4)$$

α = is the ratio of the design ground acceleration on type A ground, a_g, to the acceleration of gravity g

- S = is the soil factor
- Ta = is the fundamental vibration period of the non-structural element;
- $T1$ = is the fundamental vibration period of the building in the relevant direction
- z, H = is the height of the non-structural element above the level of application of the seismic action and building height

S_a can not be less than $(a \cdot S)$. For the following non-structural elements the important factor γ_a shall not be less than 1.5. In all other cases the importance factor γ_a of non-structural elements may be assumed to be $\gamma_a = 1.0$. Upper limit values of the behaviour factor qa for non-structural elements are given in a table in the code.

3.4. FEMA - 450 Regulation [20]

The seismic design force, F_p, applied in the horizontal direction shall be centered at the component's center of gravity and distributed relative to the component's mass distribution and shall be determined in accordance with Eq. (5) in FEMA-450 *Chapter 6.2.6* [20] as follows:

$$F_p = \frac{0.4 a_p s_{DS} w_p}{R_p / I_p}\left(1 + 2\frac{z}{h}\right) \quad (5)$$

- a_p *ve* R_p = The component amplification and response modification factors selected, as appropriate, from Tables in the code
- S_{DS} = The short period spectral acceleration parameter (It is correspond to value of "$Ao * I * 2.5$" in TDY2007)
- W_p = Operating weight of a nonstructural component
- I_p = The component importance factor
- z = The height above the base of the point of attachment of the component, but *z* shall not be taken less than 0 and the value of *z/h* need not exceed 1.0
- h = The average roof height of structure above the base

3.5. New Zealand Standard NZS 1170.5 [21]

The Code, used in New Zealand, includes design rules for curtain wall systems. Curtain wall systems are called as "part" in this code. Unlike other codes, description of the seismic force, acting on curtain wall systems is proposed even for horizantal and vertical direction in this code. These seismic forces, described in *Chapter 8.5* in the code is limited with a value which is related to the curtain wall weight. There are seismic force formulas for each direction in the code [21]. These horizantal and vertical seismic forces is described in Eqs. (6)-(8)

$$F_{ph} = C_p(T_p) C_{ph} R_p C_f(\xi)_s W_p \leq 3.6 W_p \quad (6)$$

$$C_p(T_p) = C(0) C_{Hi} C_i(T_p) \quad (7)$$

$$F_{pv} = C_{vd} C_{pv} R_p W_p \leq 2.5 W_p \quad (8)$$

- F_{ph} = Horizontal design action
- $C_p(T_p)$ = horizontal design Response Coefficient of curtain wall part
- C_{ph} = Part response factor
- R_p = Part risk factor
- $C_f(\xi)_s$ = Damping factor for support structure for (it is 1.0 for %5 damping)
- W_p = Weight of curtain wall system
- $C(0)$ = Site Hazard Coefficient for T = 0 secs
- C_{Hi} = Floor height coefficient
- $C_i(T_p)$ = Floor Spectral Shape Factor
- C_{vd} = *Vertical design factor of* curtain wall part
- C_{pv} = *Vertical design factor of* curtain wall part

There is a table for C_{ph} and C_{pv} values depended on ductility

3.6. Japanese Standard JASS14 [22]

Seismic energy is described in two ways in this Japanese standard. By the way seismic forces of a curtain wall anchorage is described also into two parts [22]. According to this standard, P and S waves are comprised of seismic energy. P waves are faster then S waves and their influence in long direction. S waves are slower then P waves and their effect in transverse. This discrimination of seismic energy is described as horizontal seismic force and vertical seismic force, similarly to NZS standard. However, there isn't given any formulas. Verbally expressed formulas are given below:

- Seismic force composed of P waves on the curtain wall system part is described as the multiplication of dead load of the part by vertical acceleration.
- Seismic force composed of S waves on the curtain wall system part is described as the multiplication of dead load of the part by horizontal acceleration.

4. MODELLING OF CURTAIN WALL SYSTEMS ON A SAMPLE BUILDING

In this section, seismic forces, effecting to anchorage elements of curtain wall system on a high rise building are acquired using various analysis method in SAP2000 software. Suggested seismic forces in various seismic codes are also calculated. Then, all the results obtained are compared on graphs.

4.1. Building, Earthquake Information and Structural System

A 30 storey regular reinforced concrete building has been choosed. Dimensions of the building are 24 x 18 m. It has one ground floor and 29 typical floors. Ground floor has 4.5 m and each storey has 3.5 m storey height. Total height of the building is 106 m. Concrete grade has been taken C40 (40 MPa) and reinforcing steel has been taken S420 (420 MPa).

A moderate service earthquake has been considered in calculations. Spectral acceleration for short periot, S_s has been taken 1.0 g and for long period S_1 is taken 0.5 g and soil type has been taken B. According to these values elastic response spectrum is given as a graph in Fig. 1.

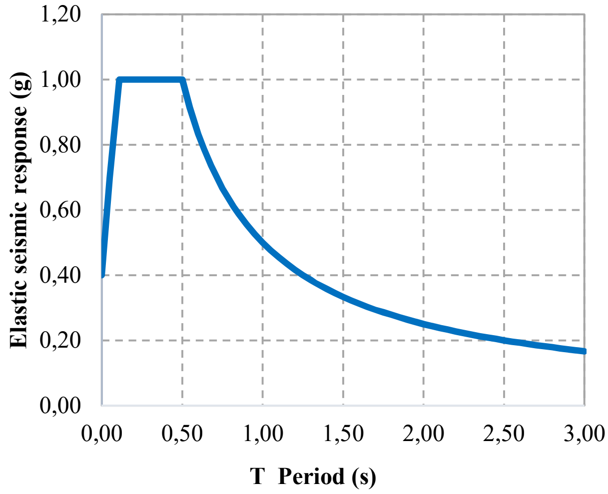

Figure 1. Used elastic response spectrum

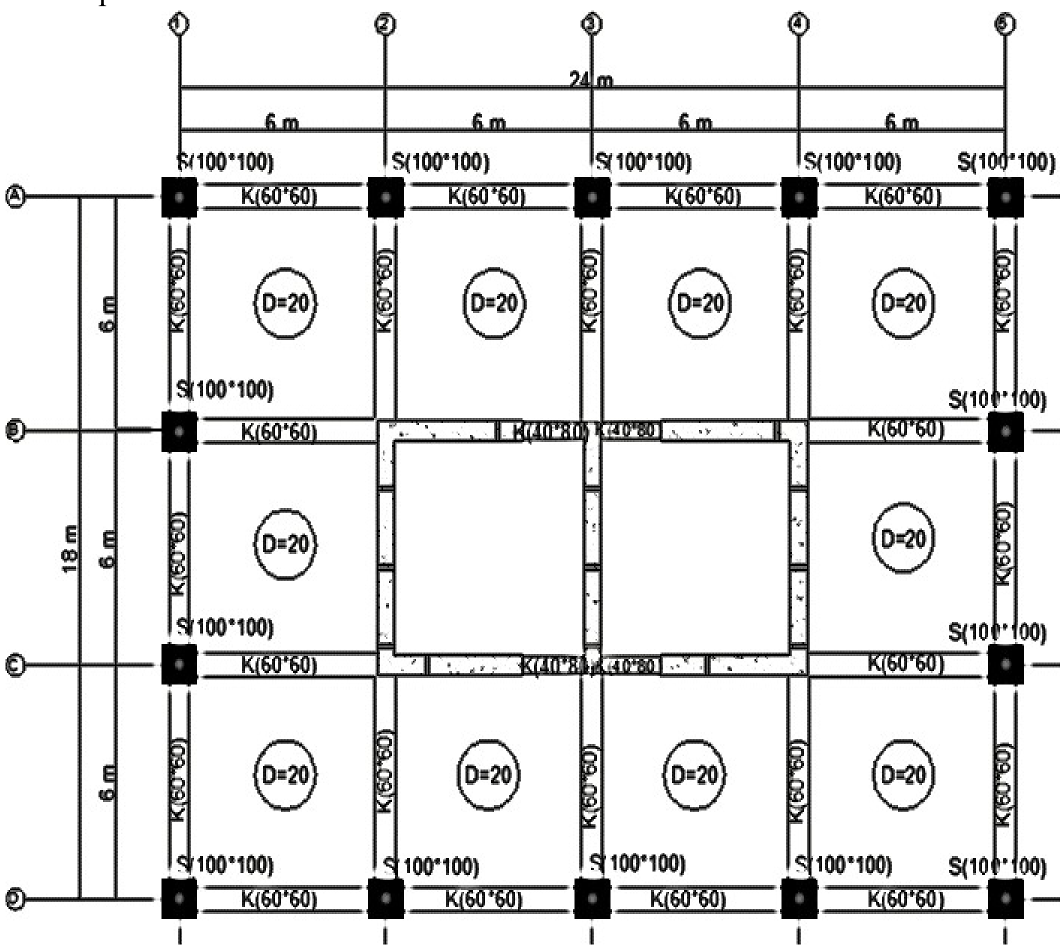

Figure 2. General floor plan (sizes are for ground)

Structural wall-frame system that has core, shear walls and columns is considered as main system. Building has 6 m axe spaces in two direction symmetrically in plan. Deck has 20 cm thickness in each floor. Core-wall at the center of building has 50 cm thickness in each floor. Beam dimensions are considered 40x80 cm at core and 60x60 cm for other beams in each floor. Column sizes vary for some storeys. Column dimensions are given in Table 1 General floor plan of sample building is given in Fig. 2.

Table 1 Column dimensions

Floors	Wide (cm)	Height (cm)
Ground - Floor 9	100	100
Floor 10 - Floor 19	90	90
Floor 20 - Floor 29	80	80

Vertical Load Acceptanses

Total dead loads, $g = 7\ kN/m^2$

Deck part $\rightarrow\ 0.2 \times 25 = 5\ kN/m^2$

Plaster + cover = $2\ kN/m^2$

Moving loads, $q = 3\ kN/m^2$

Curtain wall system loads $\cong 0.381\ kN/m^2$

4.2. Information About the Applied Curtain Wall System

Classical stick curtain wall system was choosed for analysis as alluminium material. Vertical allumunim profiles called vertical mullions were anchored by 1.5 m away between two axes in plan. Horizontal allumunim profiles called horizontal mullions were anchored by 0.75 m away from top and bottom by the way middle parts were designed as 2 m height. Profiles that were used in the system have 120 x 50 mm sizes. Spandrel panels were choosed as glass. Typical anchorage detail of the system was given at Fig. 3.

Curtain wall system loads

Vertical mullions = $22\ N/m$

Horizontal mullions = $1.97\ N/m$

Stable glass parts = $30\ N/m^2$

Sashes = $40\ N/m^2$

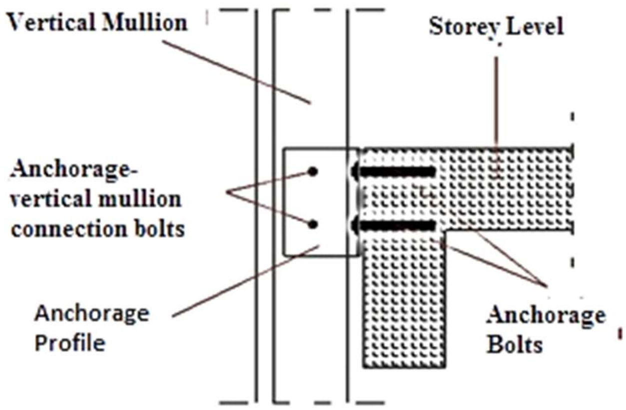

Figure 3. Typical anchorage detail of the curtain wall system

Memari, et al. [23] showed that finite-element modeling is a viable approach for analytical evaluation of curtain walls. The building was modeled using SAP2000 software. Beam and column elements were modeled as “frame”, decks were modeled as “shell-thin” and wall elements were also modeled as “shell-thin”. Two models were created for the analysis. In the first model, curtain wall system were applied as concantreated loads to each anchorage location. In the second model, curtain walls are modeled as “shell-thin” element and they were fixed to the structure with anchorage profiles which are modeled as “frame” elements. All material and gometric properties of these elements were described to the software. All columns are assumed as fixed support at bottom ends on basement. Results of second model are given below. In the future an enhancement of the FE model could be done as suggested by Amadio and Bedon [24], who also take into account the effects of possible initial geometrical imperfections.

4.3. Time History Loading and Code Loadings to the Structural System

This model called as Comprehensive model (CM), is the most comprehensive model created in this study because it contains curtain wall system and anchorage elements. Thus, it is a model in which the most realistic results can be obtained. For this reason, the results obtained from the other analysis methods and different specifications, are compared with the results obtained from this full model. As anchorage elements are modelled in this model, seismic force which must be get affected on anchorage elements during design process is the maximum force created on these anchorage elements modelled for earthquake motion get affected on model. Seven earthquake motions are applied to these structure model; when taking results, it is averaged the maximum seismic forces formed in relevant anchorage element due to the effect of these seven ground motion set. Thus, seismic force is found which needs to get affected on the relevant anchorage element during design process. As ground motions are applied in both directions (x and y), seismic forces of selected anchorage element are obtained as two compounds. Faxial is obtained for the average of ground motions applied in direction of x, Fshear for the average of ground motions applied in direction of y. In full model, aluminum is selected for material of anchorage elements and glass for material of curtain walling system. Seismic forces which will come to the curtain wall system element in full structure model are given in Fig. 4.

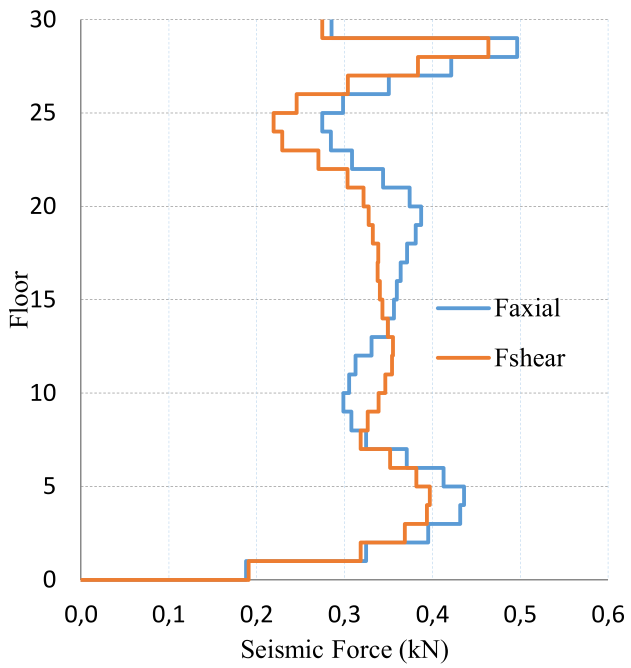

Figure 4. Seismic forces for curtain wall elements at the floor levels according to analysis methods for time history analysis.

Comparison between the force results for TDY2007, TDY2018 time history method, TDY2018 spectral analysis method, EUROCODE-8, FEMA450 loading conditions and comprehensive model (CM) are given in the Figs. 5-9 below.

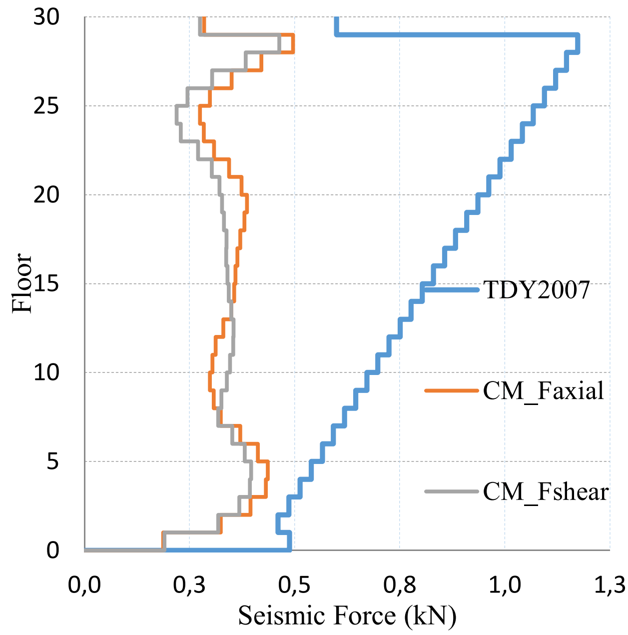

Figure 5. Comparison between the forces of TDY2007 and CM analysis

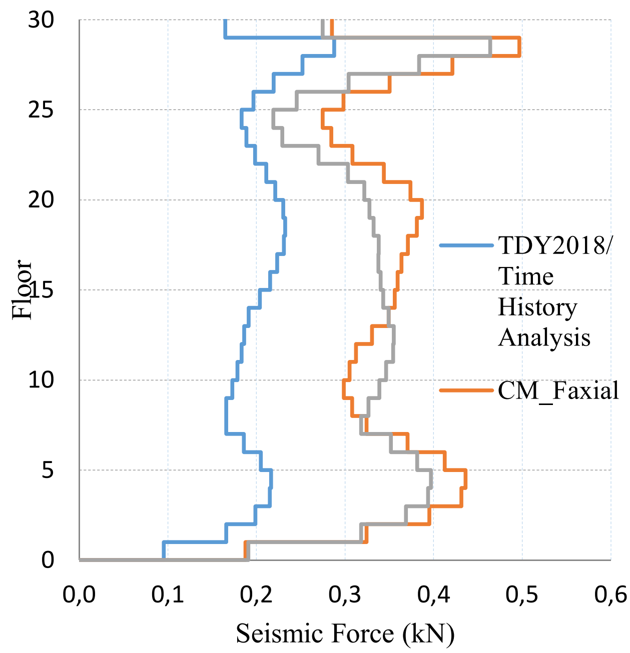

Figure 6. Comparison between the forces of TDY2018 time history analysis and CM analysis

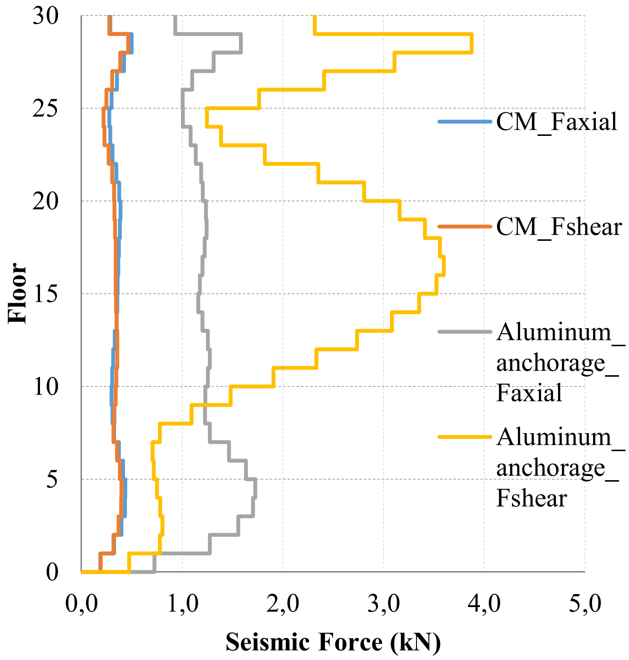

Figure 7. Comparison between the forces of TDY2018 response spectrum and CM analysis

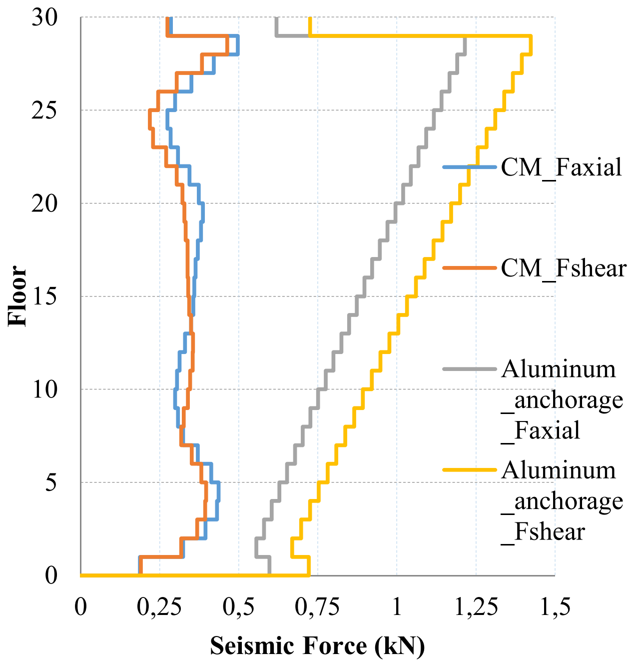

Figure 8. Comparison between the forces of EUROCODE-8 and CM analysis

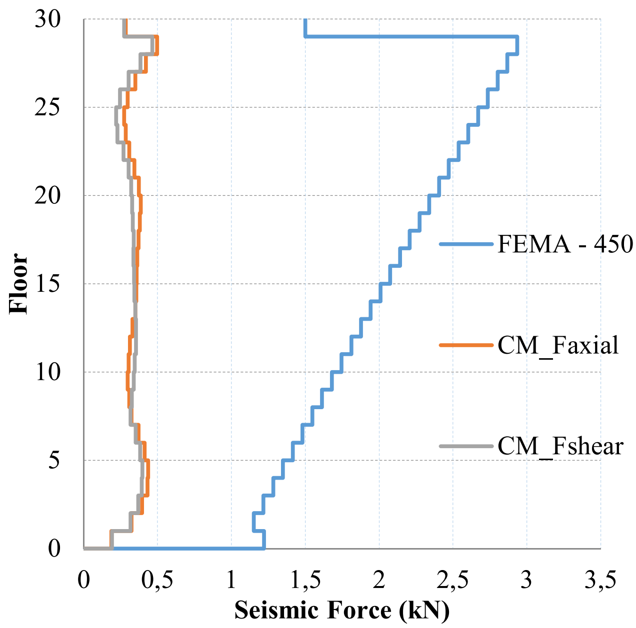

Figure 9. Comparison between the forces of FEMA-450 and CM analysis

When specifications are considered and the results are obtained, it is seen that a large part of relevant specification remains in an over secured area in relation to seismic force which needs to be get affected on curtain walling system anchorage element during design process. This mentioned security zone is defined by considering the results obtained from Comprehensive Model (CM) giving the most realistic results. It is defined as secure the specifications and methods giving bigger force values than these most realistic results. It is seen that only the results of analysis method in the field of time history situated in TDY2018, give lower values than results obtained from Comprehensive Model (CM), and curtain walling system anchorage element is not a secure method related to seismic force to be applied in design process. Besides, there are differences when it is compared the two specifications considering natural vibration period of anchorage element. The differences between especially floor 10 and 25 are big, and generally the results of TDY2018 are bigger according to Eurocode-8. When considering these two specification in themselves, pulling and cutting forces are close to each other according to Eurocode-8 Specification for two different material type. In TDY2018 Specification, this situation is valid for only pulling forces. Cutting forces results for the results of FEMA and steel anchorage profile of TDY2018 has closeness attractively between floor 15 and 20. Besides, when considering the results obtained from Comprehensive Model as the most realistic results, it can be said that FEMA Specification is over and the most secure specification in terms of seismic force to be affected on curtain walling system anchorage element.

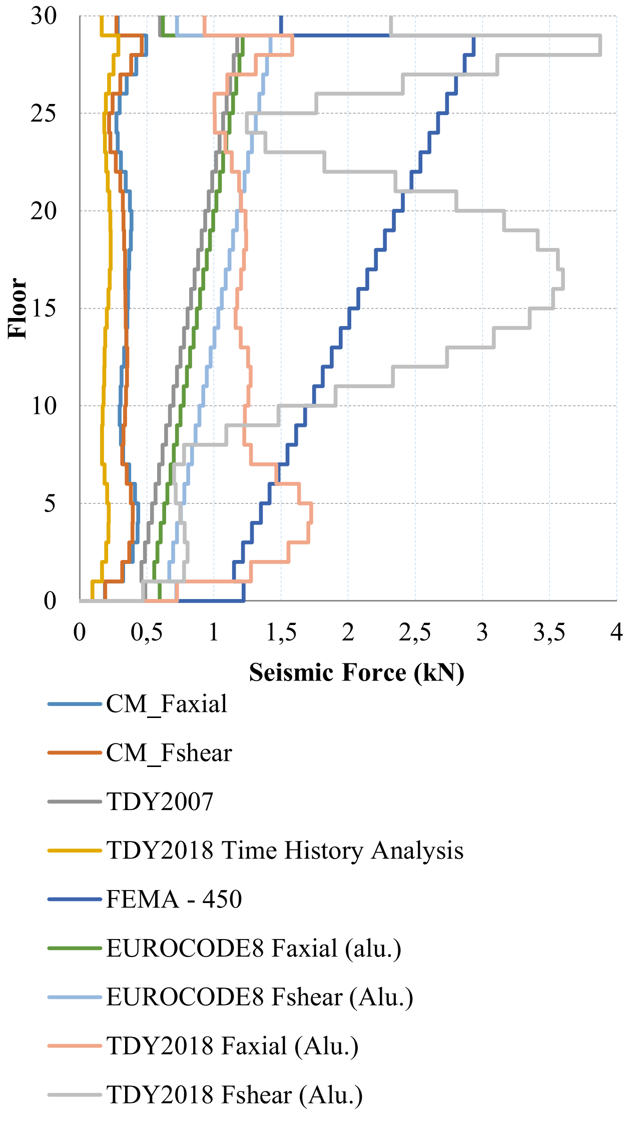

Figure 10. Comparison of the results obtained from all the regulations and CM

By remaining in security zone, TDY2007 Specification became the closest specification among used specifications to the results obtained by using Comprehensive Model (CM) accepted as the most realistic results. Because TDY2007, FEMA and Eurocode-8 Specifications do not pay attention to momentum to be occurred in floors due to the ground motions in seismic force formulas, the obtained seismic forces increase linearly toward upper floors. Because front mass decrease in half on the top floor, seismic force also decreases in half in comparison to the previous floor. It does not increase linearly the results obtained from analysis method in time history and earthquake spectrum partaking in TDY2018 and the Comprehensive Model. Because these methods pay attention to momentums occurred by ground motion, it is obtained the results of seismic force complying with these momentums. Besides, when looking at the results for relative floor translation as well as seismic force, it is seen that curtain walling system anchorage elements does not have values to cause any problem, remain low of values recommended in TDY2018 and take place in security zone in this matter. The results showing these evaluations clearly are given in Fig. 10.

5. CONCLUSIONS

The obtained results show that TDY2018 is the closest specification to the results of Comprehensive Model (CM) having the most realistic results. However, as these results obtained according to analysis method in field of time history partaking in TDY2018 have smaller values than the most realistic results, they take place in security zone. TDY2007 is the closest specification to the most realistic results by remaining in security zone. FEMA450 is the specification having the most distant results and that we can called as over secured by remaining in security zone. TDY2007 Specification come close to the closest values to the Comprehensive Model (CM) between floors 1 and 5 in the rate of 80%. FEMA450 Specification could come close at the most between floors 1 and 5 in the rate of 30%. EUROCODE8 Specification could come close to the most realistic values in all floors in the rate of 50%. TDY2018 Specification come close between floors 1 and 8 in the rate of 50%. When looking at these results, in relation to the seismic force to be paid attention during design process for curtain walling system anchorage elements, it is concluded that TDY2007 Specification gives the best and closest proposition by remaining in security zone.

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Research and Publication Ethics

This paper has been prepared within the scope of international research and publication ethics.

Ethics Committee Approval

This paper does not require any ethics committee permission or special permission.

Conflict of Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this paper.

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