EVALUATION OF SEISMIC POUNDING BETWEEN TWO ADJACENT REINFORCED CONCRETE BUILDINGS FROM ALBANIAN PRACTICE

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Approval sheet of the Thesis

This is to certify that we have read this thesis entitled **“Evaluation of Seismic Pounding between two Adjacent Reinforced Concrete Buildings from Albanian Practice”** and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ABSTRACT

EVALUATION OF SEISMIC POUNDING BETWEEN TWO ADJACENT REINFORCED CONCRETE BUILDINGS FROM ALBANIAN PRACTICE

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Seismic pounding is the colliding action between two adjacent structures that occurs during earthquake vibrations. Due to insuffiecient separation gap between buildings that own different dynamic characteristics, structural damages to both structural and non-structural elements are magnified during the impact of buildings. Since a country like Albania is considered to have moderate-size seismicity, it is important to provide and check the necessary separation distance to avoid the impact between structures. A parametrical approach is followed up in this study to evaluate the sufficient seismic gap in the middle of two existent Reincorced Concrete (RC) structures. Ten pairs of structural models are analyzed in Sap2000 by using the Equivalent Static Force Method (ESFM). The change of structural parameters such as concrete grade, seismic zone factor and storey height are inspected to study the influence they have in the separation gap between the structures. At the end, a comparison with a smilar study is done and conclusions, as well as recomandations for further studies are generalized.

Keywords: *Seismic Pounding, Separation Gap, Sap2000, Adjacent Buildings, Eurocode, Static Analysis*

ABSTRAKT

VLERESIMI I GODITJES SIZMIKE MIDIS DY GODINAVE FQINJE BETON-ARME TE NDERTUARA NE SHQIPERI

Dajko, Margarita

Master Shkencor, Departamenti I Inxhinierisë së Ndërtimit

Udhëheqësi: Assoc. Prof. Dr. Huseyin Bilgin

Përplasja sizmike është një goditje që ndodh midis dy godinave fqinje gjatë dridhjeve sizmike. Për shkak të mungeses së hapësirës ndarëse ndërmjet strukturave që zotërojnë veti të ndryshme sizmike, dëmtimet në elementet strukturorë dhe jo-strukturorë shumëfishohen gjatë goditjeve që ndodhin midis dy ndërtesave gjatë ndodhjes së një tërmeti. Përderisa Shqipëria konsiderohet të jetë ndër vendet me veprimtari sizmike nga më të lartat në Europë, është e rëndësishme të sigurohet prezenca e hapësirës së nevojshme për të shmangur përplasjen ndërmjet godinave fqinje. Në këtë studim është ndjekur një qasje parametrike për të vlerësuar gjatësinë e hapësirës ndarëse ndërmjet dy godinave ekzistuese të ndërtuara me konstruksion beton-arme. Dhjetë lloje modelesh të godinave janë analizuar në programin Sap2000, duke përdorur Metoden e Forcës Statike Equivalente. Në këtë punim është studiuar efekti që ka variacioni i parametrave të ndryshëm mbi gjatësinë e hapësirës ndarëse ndërmjet godinave fqinje. Parametrat që janë konsideruar janë: klasa e betonit, faktori i zonës sizmike dhe lartësia e kateve të godinave. Ne fund eshte bere krahasimi i ketij punimi me pune kerkimore te ngjashme per te bere vleresimin e saktesise se metodes kerkimore te perdorur.

Fjalëtkyçe: *Përplasja Sizmike, Hapësira Ndarëse, Sap2000, Godina Fqinje, Eurokod, Analizë Statike*

Dedicated to: My Beloved Family and My Country

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LIST OF ABBREVIATIONS

ABS	Absolute Sum Method
C	Concrete Class
DL	Dead Load in kN/m^2
EQ	Earthquake Loading
ESFM	Equivalent Static Force Method
FEMA	Federal Emergency Management Agency
H	Storey height in meters
LL	Live Load in kN/m2
N1	Number of Floors of Structure 1
N2	Number of Floors of Structure 2
q	Response Reduction Factor
RC	Reinforced Concrete
S_{ABS}	Separation Gap as per ABS method in cm
SG	Separation Gap in cm
S_{max}	Separation Gap as per code FEMA 356 maximum SG provisions in cm
$S_{q*(ui+uj)}$	Separation Gap as per IS1893-2016 provision in cm
SRSS	Square Root of Sum of Squares Method
S_{SRSS}	Separation Gap as per SRSS method in cm
T	Natural Period of Building
u_i	Maximum Displacement of Structure 1 at pounding location in cm
u_j	Maximum Displacement of Structure 2 at pounding location in cm
WL	Wall Load
Z	Seismic Zone Factor

CHAPTER 1

INTRODUCTION

1.1 Background

In the past, different areas, including here large cities have been witnessing severe damages and collapse of buildings due to the earthquakes. One of the consequences that results during an earthquake is the non-synchronistical vibration of adjacent buildings, which is due to the dynamic differences in the existing structures. Due to the vibration and the existence of small gaps between these existing structures, there occurs the pounding phenomenon. According to different reports and researches after several devastating seismic activities in different countries, it has been observed that pounding is present during the occurrence of strong seismic vibrations in big urban and densely populated zones. Furthermore, in some literature reviews, pounding has been recognized as the main cause for the beginning of collapse of buildings.(Favvata M. J., 2015) In many metropolitan areas, the closely built structures are a serious issue for seismic pounding destruction. (Namboothiri, 2017) For example, the damages that can cause a shallow earthquake with magnitude 5, down a metropolitan zone are far more disastrous than a deep earthquake of magnitude 7 in a distant location.

From the analysis of different collisions of adjacent structures, the insufficient gap between the existing structures is the principle reason for pounding effect. Buildings are very often constructed close to one another, as the example of residential structure complexes or in highly populated cities, due to the high price for land usage. So, for this reason, buildings have often been found to collide with each other during the response to earthquake ground motions.

The insufficient gap is not only a result of the high cost of the land, but also because the past seismic codal provisions did not provide specific guides to calculate the most probable minimum building separation needed to prevent impact. For these reasons, it is very important to find out the pounding effect of closely spaced structures during an earthquake excitation, so that there can be provided the maximum separation distance to the structures.

Albania is a developing country and urban areas are increasing their rate of population movement day by day. This means that a lot more buildings are being constructed and land usage limitation has started to be a present issue. Due to this, structures are built very close to each other and sometimes without providing the safe separation distance in-between. Furthermore, Albania is categorized as a moderate seismic country, being one of the most active seismic zones in Europe. Since buildings are prone to frequent earthquake ground motions seismic, pounding is a phenomenon that occurs whenever the safety separation distance between adjacent buildings is not provided.

1.2 Problem Statement

This study aims to estimate the minimum seismic distance between adjacent buildings using linear static analysis. The separation gap is a critical element to be considered especially for buildings constructed in urban areas, where land usage is very limited and costly. Since the lack of separation joint or insufficient separation distance between adajacent buildings has been observed in our country, this paper investigates the adequate seismic gap through the equivalent static force method (ESFM).

1.3 Objectives and scope of work

The main goal of this study is to evaluate the seismic distance between two adjacent RC buildings. Buildings represent two existent eleven and seven storey structures, modeled as two dimensional frames in Sap2000. By considering the influence of three structural paramenters (concrete class, seismic zone factor and storey height), ten buildings combinations are modeled and linear static analysis is performed for the general and fast evaluation of separation distance inbetween structures.

Assessment of separation gap is done by using four different codal approaches, including here Eurocode 8, which is implemented in recent Albanian practices. A comparison with Albanian Seismic Code (KTP-89) provisions is made, since this regulation is still in force.

The properties of earthquake loadings are selected such that they fit with the Albanian seismic characteristics.

Later, the results of the study are compared with the results of a similar study to check the accuracy of the method.

As a final point, conclusions are summarized based on the results coming from the analysis, while recommandations for an advanced future research are given.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The problem of pounding between adjacent buildings has become more and more significant due to the continuous development of construction industry, especia

lly in the urbanized metropolitan regions. Accordingly, several works, experiments and researches have been carried out to understand the occurrence this phenomenon analytically and numerically.

Namboothiri (2017) has made a generalising summary on the concept of seismic pounding by quoting that the main cause for the pounding effect is the lack of enough gap distance in between the close built structures. Then she explains the main causes of pounding, a possible method for the calculation of seismic separation distance to avoid pounding, factors affecting pounding, typical failures and damages occurring for each case of pounding and some mitigation methods utilized to reduce the damages from impact. As a conclusion, in this study it is stated that: the best way to avoid pounding is to build the structures with the necessary separation, adjacent buildings with equal floor heights and separation distances reduces the effects of pounding, at resonance state the response of the building is larger and may lead to the initiation of collapse of the whole building. (Namboothiri, 2017)

Filiatrault & Cervantes (1995) have concentrated their study in the calculation of the required separation distance between adjacent reinforced concrete wall buildings. They introduced a new method which is consistent with the code design (NBCC-1990) regulations for regular structures, where five buildings, having 3, 6, 10, 15, and 25 floors, were designed for three dystinct seismic areas in Canada: Montreal, Vancouver, and Prince Rupert. Buildings were modelled as two dimensional models with lumped mass and a microcomputer version of the code DRAIN-2D was utilized to execute the nonlinear time history dynamic analyses. The results of the dynamic analyses on ten pairs of closely built structures show that the existent separation specifications of NBCC-1990 are actually considered as conservative (with an average of over 400%). The simplified spectral difference method is proposed to replace these requirements. As a result, a procedure is utilised to anticipate in a better scale the needed separation gap. The separation distances calculated through this method are in proportion with the results from non-linear analysis. This study was conducted around 25 years ago, when there was a lack of sophisticated computer software and very simplified static methods were available in the used designing codes, so the authors emphasise at the end that extended studies are necessary to evaluate the performance of the proposed method for different categories of structures (frames, coupled walls, etc.). (Filiatrault & Cervantes, 1995)

In another study of Anagnostopoulos & Spiliopoulos (1992), pounding resulting from inadequate or lack of spacing between adjacent structures in city blocks is considered for strong earthquakes. Buildings are treated as systems with lumped-mass, shear beam type, multi-degree-of-freedom (MDOF), with bilinear force-deformation characteristics and bases are supported with translational and rocking spring-dashpots. Utilizing 5 real seismic vibrations, the influence of the next factors is inspected: structural configuration and relative size, seismic gap and impact element characteristics. In this study it is observed that seismic collision can generate large stresses, especially when impacting structures have significant differences in periods, heights and masses. This indicates again as in the previous study, an introduction of a set of requirements into the practical codes, which can be in combination with other mitigation methods, serving as an alternative to the seismic gap requirement. (Anagnostopoulos & Spiliopoulos, 1992)

Raheem, (2014) states in his study that pounding can be an issue to the closely built buildings if a seismic excitation occurs because floor accelerations and inter-story deflections are significantly amplified, threatening the functionality of the structure. His main objective and scope of study are to investigate the influence of seismic impact on the global response of structures, to define a proper earthquake hazard mitigation measure for existent structures and for new built ones, and to provide engineers with practical methods for anticipating seismic pounding behaviour and risks. Two adjacent multi-story buildings are taken into account as a representative buildings set for a potential pounding case. Seismic pounding between adjacent multi-storey structures has been designed by using a mathematical modelling. A finite element nonlinear seismic analysis is used for the implementation of the mathematical model. Furthermore, a numerical evaluation has been performed in the pounding case to generally describe impacting adjacent structures real behaviour and their influence on global structural response has been controlled. The contact force-based technique is utilized to perform an analytical approach, where the contact element is operating when the adjacent buildings are in contact with each other. By using numerical simulations, the effect of using rubber bumpers elements, attached at the positions where pounding is more likely to occur, is investigated. For the performance of the dynamic behaviour of rubber shock absorber device while pounding occurs, a nonlinear force-based impact element is used. (Raheem, 2014)

Zou, Li, Huang, and Huang (2014) have developed the analytical model of adjacent structures with unequal story height, and the equations of motion considering pounding are derived. According to analytical models, the inter-floor impact responses of adjacent structures with unequal storey height are inspected. The analytical model of pounding includes structure model, pounding element model and pounding point model. The parametrical investigations are followed and influence rules are summed up. The data obtained display that the influences of inter-floor pounding in adjacent structures on main structures are lesser than those of floor pounding. Actually the damages on impacting part are very large. Furthermore, the period ratio of buildings, the initial separation distance and the pounding position have significant effect on responses of inter-floor pounding. (Zou, Li, Huang, & Huang, 2014)

Favvata (2015) has developed his study in the essential parameters of seismic pounding and the effect they have on the shear specifications and on the ductility of the reinforced concrete buildings. The studied buildings are multi-storey RC frames elements with different total buildings heights modeled in accordance with the Eurocodes. Results show that the most essential problems for the seismic response of the RC buildings with collision issues are: the separation between the adjacent buildings, the position of the point where the column suffers the impact, the change of the number of floors between the adjacent buildings, the local response of the columns that bears the hit, the local response of the RC beam-column joints located at the level where pounding happens, the presence of masonry infill panels and their behaviour. (Favvata M. J., 2015)

In another work, Favvata (2017) has studied the correlation of the earthquake response of an existing RC frame structure at several earthquake demand degrees with the seismic gap that could be insufficient to prevent pounding hit with a closely shorter and stiffer building. 882 nonlinear step by step seismic analyses have been executed. The very first step of this paper is the assessment of the inter-storey hitting issue at 9 earthquake demand levels, utilizing for every level 14 earthquake vibrations that have been properly assigned. The cases that are treated are floor to column pounding between an 8 storey and a 3 storey reinforced concrete frame. The adjacent buildings are taken to be in contact since the in the start. The respoinse of the buildings with no seismic pounding have been evaluated as well. The sufficient required separation distance to prevent pounding between the adjacent buildings has been calculated considering two requirements: (a) prevention of the shear failure in the column that experiences the hits and (b) prevention of the contact of adjacent buildings. The seismic gap is calculated at every earthquake demand levels for pounding cases. By comparing the results with the provisions of Eurcode 8, they show less conservative spacing gap between the closely built buildings at different levels of earthquake demands. (Favvata M. J., 2017)

2.2 Causes of Pounding

Pounding is caused due to several reasons which are listed as follows:

- Adjacent structures with the same heights and storey heights (*figure 1a*)
- Adjacent structures with same storey heights but different heights (*figure 1b*)
- Adjacent buildings with differencies in total height and storey heights (*figure 1c*)
- Buildings constructed in a row (*figure 1d*)

- Adjacent parts of the same structures which are linked by one or more bridges or with dilatation joints
- Buildings having different dynamic properties, which are spaced with a distance small enough so that collision might happen
- Collision happens at the part which is not supported (e.g., mid-height) in a column or wall.
- Construction based on the earlier codal provisions for separation gap
- Potential settlement of the buildings constructed on soft soils
- Structures having irregular lateral load resisting systems in plan that might experience rotation during seismic vibrations (*figure 1e*) (Namboothiri, 2017)

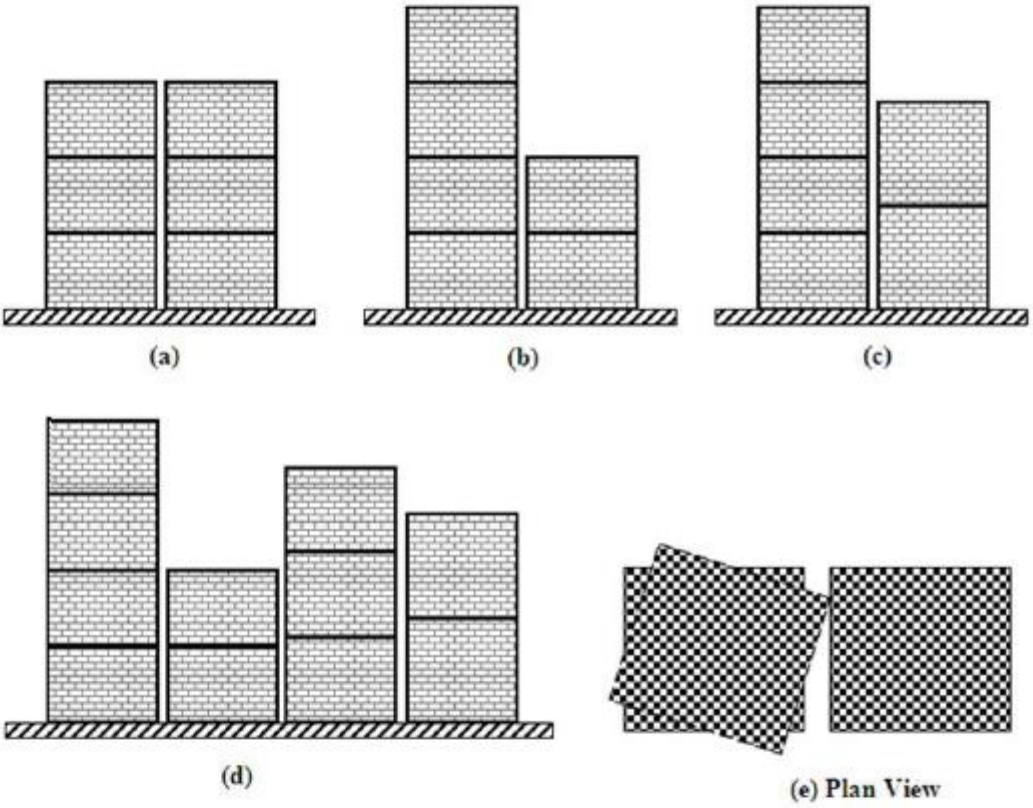


Figure 1 *Representation of different pounding cases*

2.3 Pounding Observations

In metropolitan cities worldwide, the land is congested with different types of buildings as they are built very close to each other or without any separation space at all. From the past observations, many structures have suffered serious structural damages, resulting from pounding during a seismic event.

For example: during the Alaskan seismic motion of 1964, the Anchorage Westward Hotel Tower suffered damages because of pounding with an adjoining 3-storey ballroom part of the hotel, in the San Fernando earthquake of 1971, the second storey of the Olive View Hospital struck the outside stairway, during the Mexico City earthquake of 1985, around 20 structures experienced damages because of the impact. During the seismic activity of 1989 of the Loma Prieta a pounding was observed to be very significant. Pounding occurred between 6th level of a 10-storey structure and at the roof height of an adjoining 5-storey structure, because the seismic distance was around 1.0 in. During the Chi-Chi earthquake of 1999 (*figure 2*) in central Taiwan, the structural pounding was observed in a school building. During the Bhuj earthquake of 2001, impact of adjacent buildingss was present at Ayodhya Apartments in Ahmedabad, which suffered a serious damage. Damage occurred due to inadequate separation distance between them. The Sikkim earthquake of 2006 caused damage to the walls and columns of a 9-storey masonry infill reinforced concrete frame building at Sikkim Manipal Institute of Medical Sciences Tadong, Gangtok. During Niigata Chuetsu-Oki Japan earthquake of 2007, damages happened when the adjacent buildings had slabs positioned at different elevations and insufficient spacing distance in between. During the Wenchuan earthquake of 2008, pounding damage was observed in Hanwang town, where a two-storey building collided with an adjacent three-storey building and collision occurred just below the slab level. During the recent Sikkim earthquake of 2011, pounding damage was observed at unequal slab levels of adjacent buildings. Pounding damage was not only observed in buildings but also in bridges; two bridge decks collided and caused severe structural damage. (Rajaram & Kumar, 2012)
In Europe, pounding has been observed during the L’Aquila earthquake of 2009 (*figure 4*), during the earthquake in Athens, in 1999, etc. (Sołtysik, Falborski, & Jankowski, 2017)

In Albania, the latest severe earthquake was the one that happened in November 2019, in Durres. Pounding has been observed between adjacent structures (*figure 5).* The separation and fall of plaster from masonry walls close to pounding location between RC buildings is observed. (*figure 6).* The phenomena of pounding for these cases resulted in impact and formation of a gap at the upper levels of the buildings (*figure 7).* This kind of damage was resulting from the occurrence of the lowest mode of vibration (first mode). This phenomenon occurs generally in stiff buildings. Pounding damages have been observed in Tirana as well during the November 2019 earthquake (*figure 8) & (figure 9).* Similar pounding damages occurred as in Durres building. This similarity indicates that a lot of buildings in Albania are quite flexible identified especially by absence of stiffening elements, shear walls etc. (Lekkas, Mavroulis, Filis, & Carydis, 2019)

Figure 2 *Bridge Pounding in 1999 Chi-Chi Earthquake* ***(Sun, Li, Bi, Chouw, Butterworth, & Hao, 2011)***

Figure 3 *Buildings Pounding in 2009 New Zeland Earthquake* ***(Khatami, Far, & Karimi, 2014)***

Figure 4 *Buildings Pounding in 2009 L'Aquila Earthquake* ***(Raheem, 2014)***

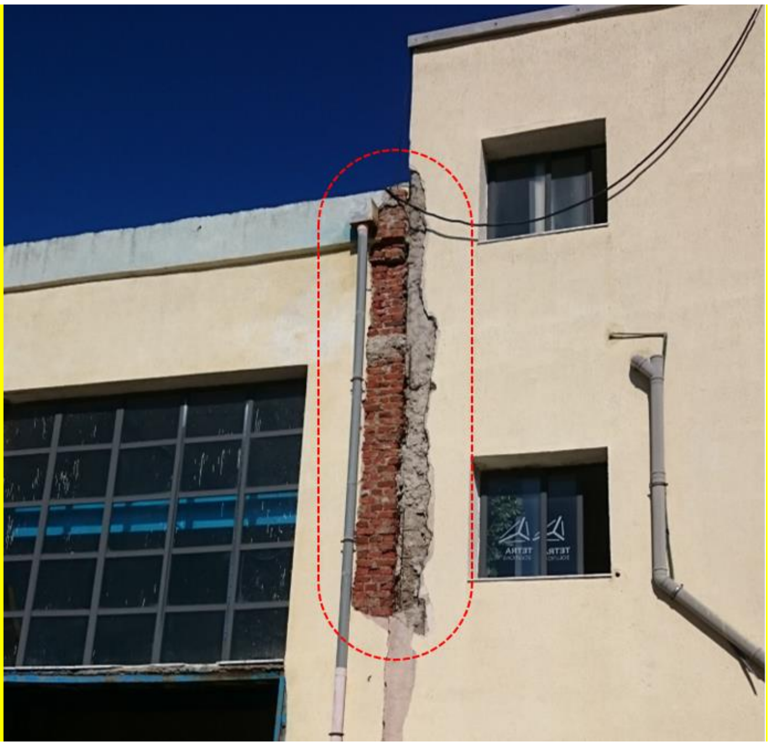


Figure 5 *Pounding failure due to lack of dilatation joints* ***(Bilgin, Leti, Hysenlliu, & Bidaj, 2020)***

Figure 6 *Pounding development due to higher modes of vibration in Durres Earthquake of 2019* ***(Lekkas, Mavroulis, Filis, & Carydis, 2019)***

Figure 7 *Pounding development due to the lowest mode of vibration in Durres Earthquake of 2019* ***(Lekkas, Mavroulis, Filis, & Carydis, 2019)***

Figure 8 *Pounding development in Tirana during the Durres Earthquake of 2019* ***(Lekkas, Mavroulis, Filis, & Carydis, 2019)***

Figure 9** Pounding development in Tirana during Durres Earthquake of 2019* ***(Lekkas, Mavroulis, Filis, & Carydis, 2019)

2.4 Codal provisions for minimum separation distance

A large percentage of provisions for earthquake design do not consider the seismic pounding very significantly. Some exceptions include the codes of Taiwan, Indonesia, Argentina, Australia, USA, Canada, France, Mexico, Greece, Turkey, Canada and India. These regulations provide a minimum seismic gap separation in the middle of adjacent structures. Methods used for the evaluation this gap are different from code to code because of the needs to calculate reliable and economic separation. (Rajaram & Kumar, 2012)

The square root of the sum of squares (SRSS) and the absolute sum method are the most elementary formulae and they are implemented in seismic codes such as **IBC**, *International Building Code*. The formulas of these approaches are as follows:

$$\boldsymbol{SG = u_i + u_j} \qquad \textbf{\textit{Equation 1}}$$

$$\boldsymbol{SG = \sqrt{u_i^2 + u_j^2}} \qquad \textit{Equation 2}$$

where, SG is the separation gap, u_i and u_j are the peak lateral displacements of buildings i and j, respectively.

Meanwhile, in some other codes the heights of adjacent buildings are taken into consideration while calculating the separation gap. One of the examples is the **Iranian Code of Practice for Seismic Resistant Design of Buildings**, where the formula is the following:

$$\boldsymbol{SG = 0.05(h_i + h_j)} \qquad \textit{Equation 3}$$

According to Jeng et al. the separation gap formula is given based on the SRSS formula:

$$\boldsymbol{SG = \sqrt{u_i^2 + u_j^2 - \rho_{op} 2 u_i u_j}} \qquad \textit{Equation 4}$$

where ρ_{op}, represents the cross correlation coefficient that reflects the vibration phase between two elastic buildings. ρ_{op} can be calculated as:

$$\boldsymbol{\rho_{op} = \frac{8\sqrt{\zeta_i\zeta_j}\left(\zeta_j+\zeta_i\left(\frac{T_j}{T_i}\right)\right)(\frac{T_j}{T_i})^{3/2}}{(1-((\frac{T_j}{T_i})^2))^2 + 4\zeta_i\zeta_j(1+\left(\left(\frac{T_j}{T_i}\right)^2\right)\left(\frac{T_j}{T_i}\right)+4({\zeta_i}^2+{\zeta_j}^2)\left(\frac{T_j}{T_i}\right)^2}} \qquad \textit{Equation 5}$$

where T_i and T_j are the vibration periods of structures i and j respectively, while ζ_i andζ_j represent the structural damping ratios. (Khatami, Naderpour, Barros, & Jankowski, 2019)

The Indian Standard IS 1893:2016 states that the seismic gap between two adjacent structures is equal to the response reduction factor (which in Eurocode 8 is denoted by letter “q”) times the sum of floor displacements u_i and u_j of the buildings.

The default value of the reduction factor in Eurocode 8 for R/C ductile buildings is equal to 6, while in the Albanian Earthquake Resistant Design Regulations 1989, the reduction factor is 5. (Sanchez-Ricart, 2010)

The **Taiwan code** represents another case of such a state where the neccessary seismic gap to prevent pounding is calculated based on the height of the structures without including the calculation of the maximum displacement.

Peru Code for earthquake design utilizes values of maximum displacements of the adjacent structures and heights of buildings as references. The separation gap is calculated by using the following formula:

$$\boldsymbol{SG_{min} = \frac{2}{3}(u^L_{max} + u^R_{max})} \qquad \textit{Equation 6}$$

The calculated distance should not be lower than:

$$\boldsymbol{SG = 3 + 0.004(h - 500)} \qquad \textit{Equation 7}$$

where *h* is the height of the shorter structure (in cm). (Jankowski & Mahmoud, 2015)

According to Federal Emergency Management Agency (FEMA 356), minimum seismic gap for adjacent buildings is calculated with the SRSS formula. The value of the separation gap should be less than 4% of the height of the level under consideration above grade at the position where the potential pounding might occur.

Seismic Code of Turkey (2007) The length of the seismic gap should not be smaller than the sum of the mean floor displacements, times the coefficient α, where α = R/4, if the storey heights of the adjacent buildings are; and α = R/2 if any of the storey heights of the adjacent structures or block of structures are not the same, where R is the structural behaviour coefficient (Seismic code of Turkey, 2007). Storey displacements taken into account are the mean values of the ones computated within a floor at the column or structural wall joints. For all cases minimum separation gaps should be 30 mm up to 6 m height. From there on, a minimum 10 mm should be added for each 3 m height increase. (Eletrabi, Abdel-Mooty, & Ghouneim, 2010)

The Egyptian code of practice and the **Eurocode 8** employ formula of the square root of the sum of squares (SRSS). (Abdel-Mooty, Raafat, & Zaki, 2016)

During the past 50 years, most of structures in Albania have been designed according to Albanian national code. The code was lastly updated in 1989 and it is still in force **(KTP-89)**, as due to Albanian legislation in the construction field, the construction of buildings still must have to follow the **KTPs (Albanian Technical Codes)**. The implementation of Eurocode standards has initiated only during the past few years. Many constructing firms have included Eurocodes in their practice, but still Eurocodes can be used voluntarily. According to KTP-89, the minimum seismic joint is calculated with the following formula (Qendra Sizmiologjike & Drejtoria e Projektimeve, 1989):

$$SG = u_i + u_j + 2cm \qquad \textbf{Equation 8}$$

where SG is the separation gap, u_i is the maximum displacement of building 1 and u_j is the maximum displacement of building 2.

According to KTP-89, the SG should fulfil the followings:

$$SG \geq h/250 \text{ and } SG \geq 3cm \qquad \textit{Equation 9}$$

where h is the height of the shortest building.

***Table 1** Building seismic gap between two adjacent buildings from different country code provisions*

No.	Country	Formula
1	UBC 1997	SG $= \sqrt{u_i^2 + u_j^2}$ ...(Adjacent Buildings located on the same property line) (Clause 1633.2.11)
2	IBC 2009	$SG = \frac{C_d u_{max}}{I}$
3	ASCE: 7-2010	$SG = \frac{C_d u_{max}}{I}$
4	AS 1170.4-2007	The separation between adjacent buildings to be at least 1% of the building height.
5	India (IS: 1893-2002)	R times the sum of the calculated storey displacements using design seismic forces to avoid damage of the two structures when the two units deflect towards each other. When the two buildings are at the same elevation levels, the factor R may be replaced by R/2. (Clause 7.12.3)
6	NBC Peru E030-2003	This minimum distance not be lower than 2/3 of the sum of the maximum displacement of adjacent blocks nor lower than $S=3+0.004(h-500)$. (Clause 3.8.2)
7	Eurocode 8	SG $= \sqrt{u_i^2 + u_j^2}$
8	The Egyptian Code	SG $= \sqrt{u_i^2 + u_j^2}$
9	Seismic Code of Turkey (2007)	Sizes of gaps shall not be less than the sum of the values of average storey displacements multiplied by the coefficient α, where α = R/4 if all floor levels of adjacent buildings or building blocks are the same; and α = R/2 if any of the floor levels of adjacent buildings or building blocks are not the same, in which R is the structural behaviour factor.

2.5 Methods of seismic analysis of a structure

Due to the rapid increase of the number of sophisticated and user – friendly software, seismic analysis has been used increasingly in both research and practice. Generally, analysis applied in elastic and inelastic response analysis is performed either by static or by dynamic methods. Normally, dynamic analysis is more realistic and is the most natural performance for the evaluation of seismic response, but as it has a greater scale of complication; it needs more computational efforts and interpretation of results compared with the static analysis. (Elnashai & Sarno, 2008)

For a moderate evaluation of earthquake response, the linear state of stress is mostly used. While in case of a more complicated or of a higher importance structure, it is more preferable to utilize non-linear method. In Eurocode 8 there are defined four methods of analysis:

- Lateral force method,
- Modal response spectrum analysis,
- Non-linear time-history (dynamic) analysis,
- Non-linear static (pushover) analysis.

For more adequate results of the seismic response of the structure, it is recommended to utilize one of the non-linear methods. Amongst properties for a non-linear computation, ductility is the most important, as it gives information for the response of plastic deformations, which are irreparable. Actually, this can be applied to lower the earthquake loading. (Sharma, 2008)

2.5.1 Lateral force method

This method is a static and linear (linear response of the material) evaluation, in which lateral forces are considered as earthquake load. Moreover, the base shear force can be defined in every direction and distribution of lateral forces is linearly growing. Each floor of the building must be rigid in their plans. (Čada & Máca, 2017)

2.5.2 Modal response spectrum analysis

The behaviour of multi degree of freedom systems to a transient signal can be evaluated breaking down the system into series of single degree of freedom systems, evaluating individually the behaviour of every system in the time domain and then adding together the response history to acquire the response of the multi degree of freedom system. This is the general procedure for modal analysis. In case only the maximum response quantities are required, then modal maxima are obtained and they are put in combination to have a maximum response of the multi degree of freedom system. In this case, this method of analysis is called the modal spectral analysis.

2.5.3 Non-linear time-history analysis

The differential equation of motion is integrated with the direct numerical method in the non-linear time-history analysis. Using this integration method, the analysis has more accuracy and it provides a lot more information for any seismic motion. With the application of a time dependent forcing function, the response-history of the building during the seismic vibration is assessed. The direct step-by-step method for the evaluation of both linear and non-linear inelastic response is included in different computer software. SAP2000 is one of the software that incorporates this method, where 3D non-linear analyses are performed and three orthogonal accelerogram components are derived as input from a specific earthquake and they are applied together to the structure.

2.5.4 Non-linear static analysis

This method is also called as pushover analysis and it is a simplified method for the evaluation of the strength capacity in the post-elastic range. In this approach, a lateral load pattern is defined and then it is distributed throughout the structure’s elevation. The lateral forces are increasing with a constant rate with a displacement control node of the structure up until a degree of deformation is obtained. Then, the graph of the applied base shear and the related lateral displacement at every loading increment is made. A target displacement that is an approximate of the displacement that the design earthquake will induce on the building is evaluated.

CHAPTER 3

METHODOLOGY

3.1 Structural Modelling

Two existing RC adjacent structures with different heights, G+11 and G+7, with an initial separation gap of 10 cm, are considered for the study of the effect of pounding under seismic loadings (*Figure 10*). The selected buildings are located in the city of Korca and they serve as residential structures. According to Department of Seismology of the Institute of Geosciences, Korca is one of the highest seismic zones in Albania (*Figure 11*) where during the last earthquakes, several buildings have suffered serious damages, as in the case of the earthquake of June 2019.

Figure 10 *Front view of the adjacent buildings*

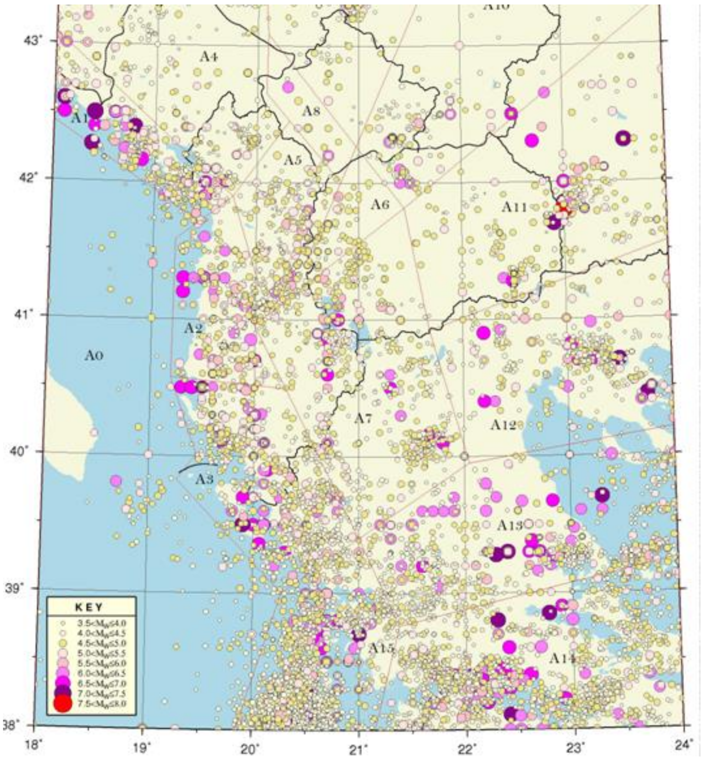


Figure 11 *Earthquake epicenter distribution in Albania and surrounding area (31/12/2008)* ***(Fundo, Duni, Kuka, Begu, & Kuka, 2012)***

Since pounding can be a cause for the amplification of structural damages, the parametrical studies are carried to evaluate the minimum separation gap between two mid-rise buildings.

The FEM analysing software SAP2000 is used to design the representing 2D frame structures and run the analysis. Sap2000 is capable to anticipate the geometric non-linear behaviour of RC frames of buildings subjected to dynamic or static loadings. In the run of analyses, both geometric nonlinearity and material inelasticity are considered. Sap2000 acknowledges static actions and dynamic loading cases and it can to run to different categories of analysis such as non-linear static pushover eigenvalues, and non-linear dynamic analyses.

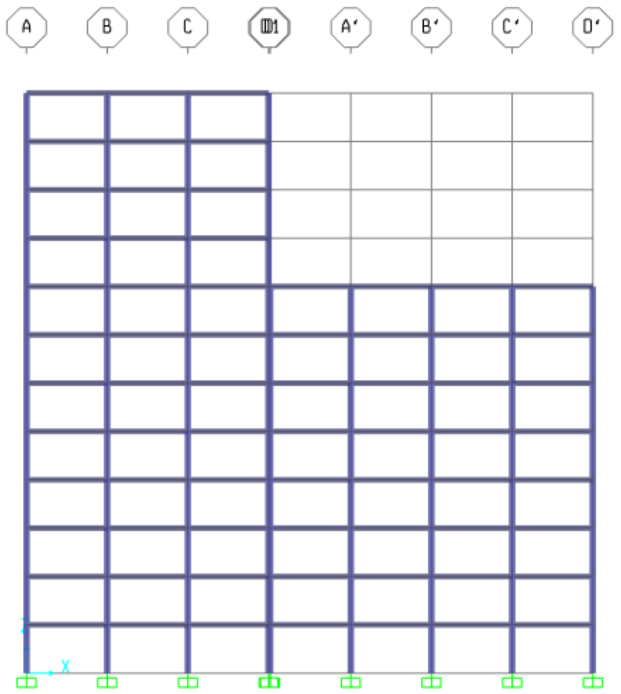
3.2 Selection of Buildings and Modeling Parameters

Buildings which are modelled are two symmetric eleven storey and seven storey RC residential buildings with equal storey height. Both buildings are designed as 2D frame models with fixed supports at the ground level. Sap2000 v.16.0.0 is utilized to run the linear static analyses.

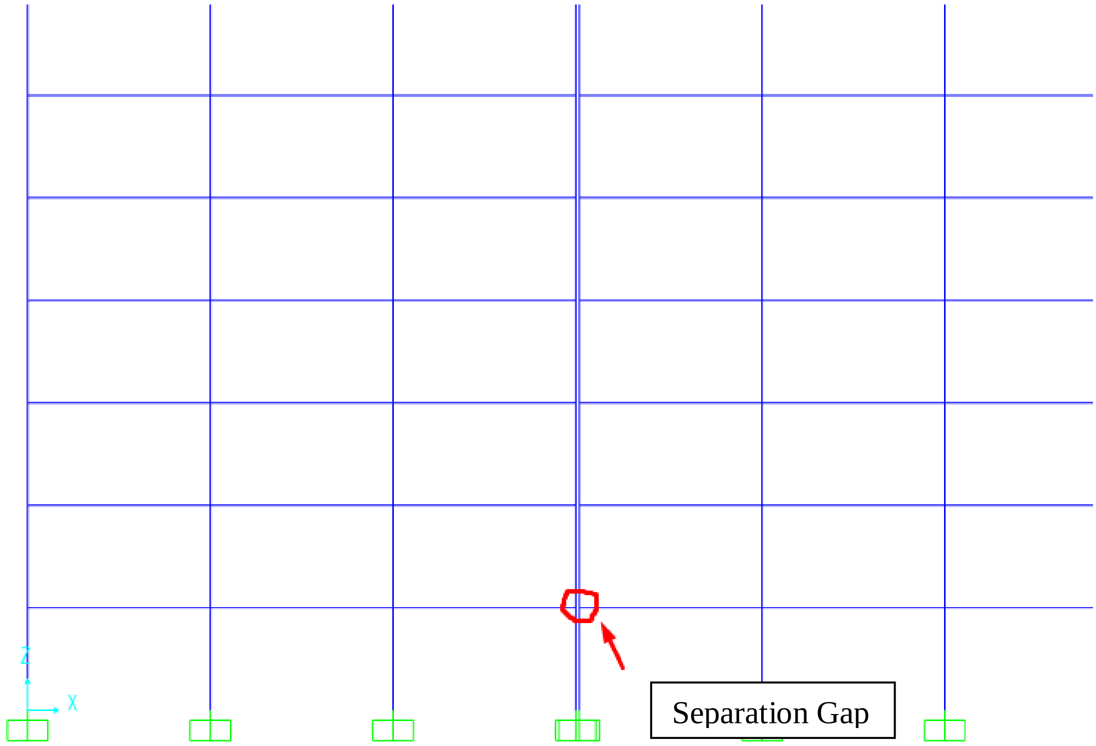
For this study, a parametric approach is followed, where the systems of structures are analysed in three general cases. The variables considered to evaluate the the separation gap (SG) are the concrete class, seismic zone factor and storey height. In the first case, three distinct concrete classes (C) are considered as follows, C20/25, C25/30 and C30/37. For two other cases C is taken as C25/30. While, for the second case, the influence of the seismic zone factor (Z) on separation gap is taken into consideration. The selected factors are 0.30, 0.25, 0.20 and 0.15. The seismic zone for the first and the third case is taken as 0.25, as Korca is rated as an active seismic zone in Albania. Lastly, for the third case, the change of SG with the storey height is observed, where three different storey levels 2.8m, 3.0m and 3.5m are chosen. The height (H) of every column is considered to be the vertical floor to floor distance. The heights of each storey are considered to be the same in both structures. For the first and the second case, the heights are 3.0 m.

3.3 Structural Elements Design

Two representative R/C frames of structures are modelled in Sap2000 by using the technical plans of the buildings. Frames consist of columns with (40cm x 40cm) dimensions and beams with (35cm x 30 cm) dimensions. The number of bays in y direction for the 11-th storey frame is 3, with 5 m spacing each (*Figure 12*). Meanwhile, for the 7-th storey building the number of bays is 4, where the width of each bay is 5 m. The frame is assumed to be resting on soil of class C, according to Eurocode classifications.



(a)



(b)

Figure 12 *(a) Two dimensional frame structures modeled in Sap2000 (b) Separation Gap between structures*

Cross section reinforcement of the elements is designed according to Eurocodes' requirements. Steel bar class is S500. The thickness of the slabs is considered to be 15 cm. The concrete unit weight is taken as 25 kN/m^3. After the properties of materials are defined, "Section Designer" command is utilized to design the details of reinforcement for columns and beams. Section Designer is a separate tool built into SAP2000 that can be utilized to design specific frame section properties. It allows sections of arbitrary geometry and combinations of materials to be created. Unlike default frame sections built in SAP2000, which allows the usage of only one main material (concrete), in Section Designer it is possible to create a section with different concrete material properties and precise disposition of rebars (*Figure 13) & (Figure 14)*. (Salihovic & Ademovic, 2018)

For the section design, a rectangular solid shape with centre coordinate (0, 0) is drawn. Then, the height, width of column and rebar material are defined (units of dimensions are in cm). Based on the technical specifications, concrete cover is 2.5 cm. The position of every centre of the circular reinforcement bars is defined by using reference lines. The number of steel bars, the spacing distance between each bar and the diameters are specified in columns construction plan.

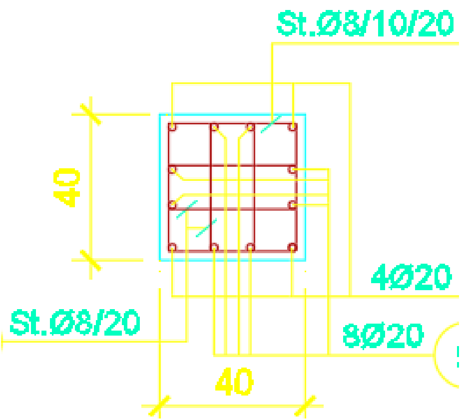


Figure 13 *Column section details*

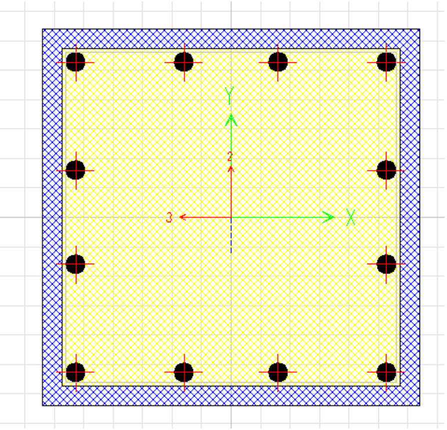
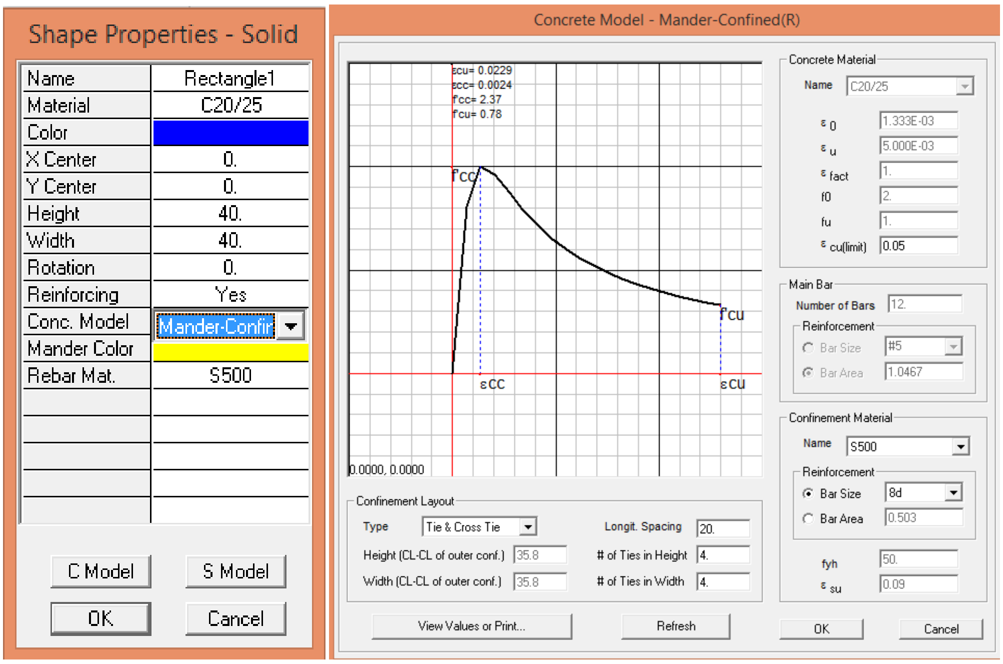


Figure 14 *Column section designed with Section Designer in Sap2000*

The shear reinforcement effect for beams is not calculated during the analysis in Sap2000. So, only vertical elements will be designed for the confinement reinforcement by utilizing the Concrete Model “Mander-Confined (R)”. Based on the technical plans and details of both buildings, the confinement reinforcement is designed by specifying the confinement material, reinforcement bar size and shear links spacing (*Figure 15*). The stress-strain curve for column concrete is considerably affected when the shear reinforcement is included.


Shape Properties - Solid

Name	Rectangle1
Material	C20/25
Color	🟦
X Center	0.
Y Center	0.
Height	40.
Width	40.
Rotation	0.
Reinforcing	Yes
Conc. Model	Mander-Confir
Mander Color	🟨
Rebar Mat.	S500

Concrete Model - Mander-Confined(R)

Concrete Material
Name: C20/25
ε_0: 1.333E-03
ε_u: 5.000E-03
ε_{fact}: 1.
f0: 2.
fu: 1.
$\varepsilon_{cu(limit)}$: 0.05

Main Bar
Number of Bars: 12.
Reinforcement: ○ Bar Size #5 ● Bar Area 1.0467

Confinement Material
Name: S500
Reinforcement: ● Bar Size 8d ○ Bar Area 0.503
fyh: 50.
ε_{su}: 0.09

Confinement Layout
Type: Tie & Cross Tie
Longit. Spacing: 20.
Height (CL-CL of outer conf.): 35.8
# of Ties in Height: 4.
Width (CL-CL of outer conf.): 35.8
# of Ties in Width: 4.

εcu= 0.0229
εcc= 0.0024
f'cc= 2.37
f'cu= 0.78

Figure 15 *Column section confinement design with Section Designer in Sap2000*

The design procedure for the reinforcement of beams is approximately the same as for the columns. No confinement is included for the concrete.

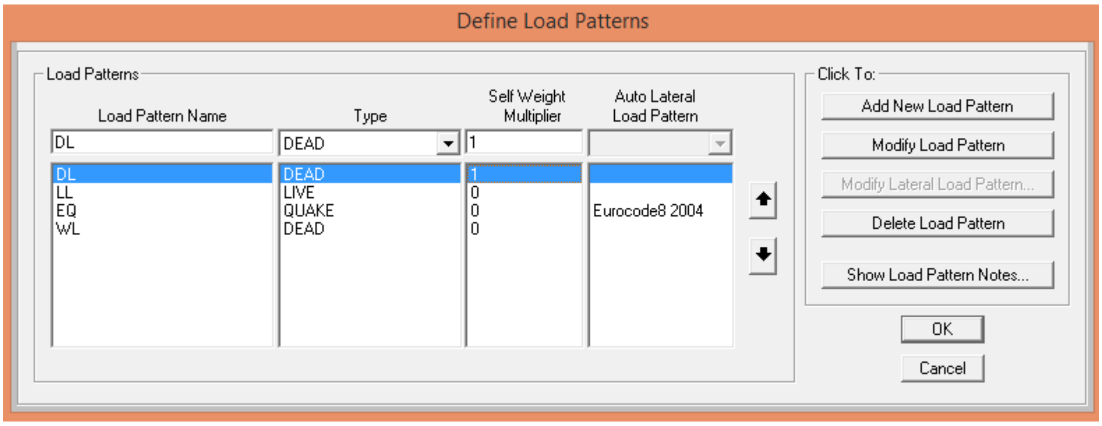
After the frames of both buildings are drawn in Sap2000, load patterns are defined (*Figure 16*). The frames are loaded under the dead loads (DL), live load (LL), wall load (WL) and earthquake loads (EQ). According to Eurocode, the loads are combined as in the following equations:

$$\boldsymbol{DL + EQ} \qquad \textbf{\textit{Equation 10}}$$

$$\boldsymbol{DL + EQ + 0.3LL} \qquad \textbf{\textit{Equation 11}}$$

$1.35DL + 1.5LL$ ***Equation 12***

$DL + 1.5LL$ ***Equation 13***



Load Pattern Name	Type	Self Weight Multiplier	Auto Lateral Load Pattern
DL	DEAD	1	
DL	DEAD	1	
LL	LIVE	0	
EQ	QUAKE	0	Eurocode8 2004
WL	DEAD	0	

Figure 16 *Load pattern definition in Sap2000*

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Analysis and Results

In this paper, all two dimensional representing models and analysis are performed in Sap2000. Structures are loaded under DL, LL and EQ combinations, as it is indicated in Euro 2-2004. Different evaluations for SG through square root of the sum of squares method (S_{SRSS}), absolute sum method (S_{ABS}), IS1893, 2016 provision $S_{q*(ui+uj)}$ and FEMA 356 maximum SG S_{max}, are done. The calculations for each evaluation methods for SG are tabulated in the table. N_1 and N_2 are the numbers of storeys of the first structure and second building, respectively.

From the results in the table, the SRSS method estimates the minimum values of SG, but it is not an adequate approach to follow in case out of phase vibrations occur simultaneously. So, for a safer evaluation, the S_{ABS} method is used to calculate the optimal SG. The $S_{q*(ui+uj)}$ and S_{max} give overestimated amount of SG, which is not convenient due to limitations of land usage. So, for the graphs and results, the S_{ABS} numerical values are used. The SG provision calculation according to KTP-89 is also evaluated, to check and compare the results with Eurocode and other provisions.

Table 2 *Calculation for Separation Gap*

Building Combination	***C***	***Z***	***H***	***N1***	***N2***	S_{ABS} ***(cm)***	S_{SRSS} ***(cm)***	$S_{q*(ui+uj)}$ ***(cm)***	S_{max} ***(cm)***
1	20	0.25	3.0	12	8	11.3907	8.967373	68.3442	96
2	25	0.25	3.0	12	8	11.2834	8.896947	67.7004	96
3	30	0.25	3.0	12	8	11.2322	8.840752	67.3932	96
4	25	0.30	3.0	12	8	13.6723	10.76199	82.0338	96

5	25	0.25	3.0	12	8	11.2834	8.896947	67.7004	96
6	25	0.20	3.0	12	8	8.987	7.072979	53.922	96
7	25	0.15	3.0	12	8	6.8367	5.3795	41.0202	96
8	25	0.25	2.8	12	8	9.2692	7.292811	55.6152	89.6
9	25	0.25	3.0	12	8	11.2834	8.896947	67.7004	96
10	25	0.25	3.5	12	8	13.3747	10.68654	80.2482	112

where C is concrete class, Z is seismic zone factor, H is storey height, N1 is the number of storeys for building 1 and N2 is the number of storeys for building 2

Table 3 *Calculation for Separation Gap according to KTP-89*

Building Combination	***C***	***Z***	***H***	***N1***	***N2***	***KTP-89 (cm)***
1	20	0.25	3.0	12	8	13.3907
2	25	0.25	3.0	12	8	13.2834
3	30	0.25	3.0	12	8	13.2322
4	25	0.30	3.0	12	8	15.6723
5	25	0.25	3.0	12	8	13.2834
6	25	0.20	3.0	12	8	10.987
7	25	0.15	3.0	12	8	8.8367
8	25	0.25	2.8	12	8	11.2692
9	25	0.25	3.0	12	8	13.2834
10	25	0.25	3.5	12	8	15.3747

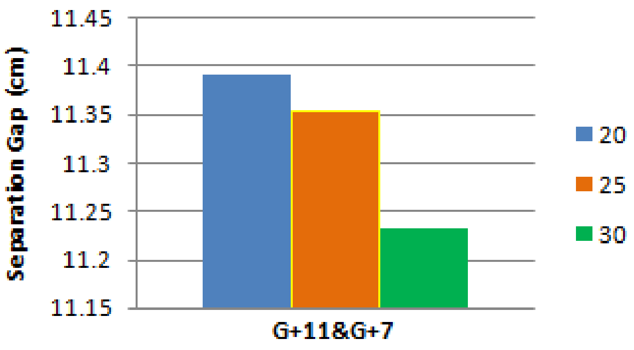


***Figure 17** Variation of SG with concrete class*

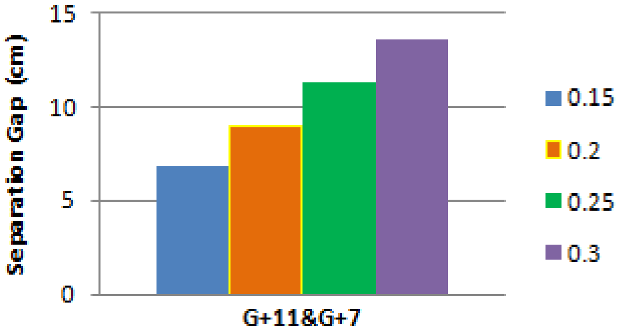


***Figure 18** Variation of SG with seismic zone factor*

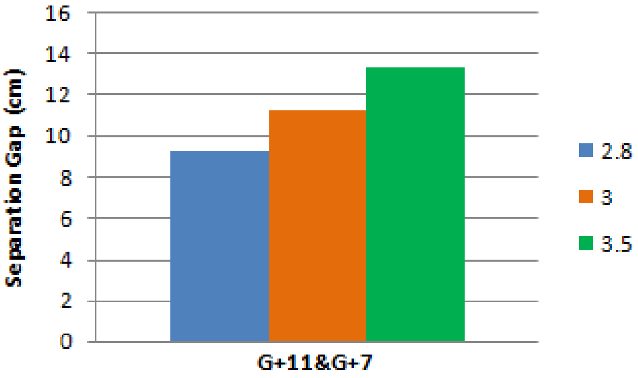


***Figure 19** Variation of SG with storey heights*

By comparing all the results coming from the cases, the most critical case is considered the one with the highest seismic zone factor. Due to the large impact, both buildings suffer greater damages during the earthquake. So, in order to prevent serious damages, the provision of sufficient SG is very crucial while designing adjacent structures.

The natural period of the tallest RC building is used to check the correctness of every model by making the comparison with Eurocode 8 specifications. In the table below, there is shown the natural period of the tallest buildings for each corresponding building confirmation in Sap2000 and every model is checked to be matching with Eurocode requirements. (Inel, Ozmen, & Cayci, 2019)

$$T=0.075H^{0.75} \qquad \textbf{Equation 14}$$

Table 4 *Periods of the higher structure*

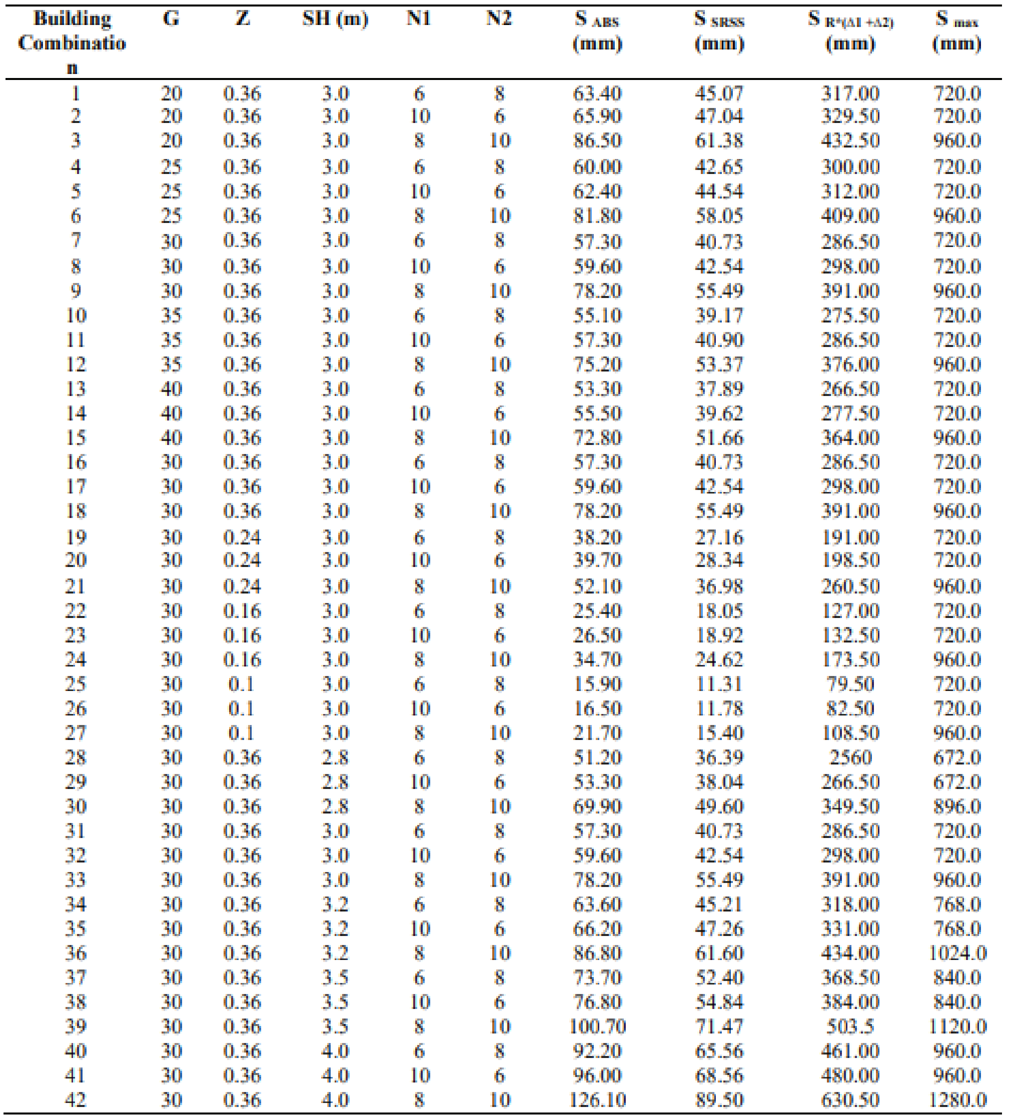
Building Combination	***T (s)***
1	1.0
2	1.0
3	1.0
4	1.0
5	1.0
6	1.0
7	1.0
8	0.9
9	1.0
10	1.2

4.2 Studies comparison

In a similar study by Saxena et al. for the evaluation of the seismic spacing gap in the middle of two reinforced concrete structures, the change that the needed gap experiences with the change of structural parameters such as concrete class, zone factor and storey height is observed. Three different RC buildings (6 storey, 8 storey and 10 storey) are combined two by two. In that study it has been observed that by increasing the concrete grade, the SG between close structures lowers. By increasing Z from 0.16 to 0.24 and 0.24 to 0.36, the increase is 50%. As H increases from 2.8m to 3m and 3m to 3.2m, the SG respectively increases by 11.9% and 11%. (Saxena, Ghosh, & Debbarma, 2019)

Similarily, in this study the same tendency occurs with SG, eventhough the percentages of changes are different. By analysing the first case, it can be noticed that by increasing the concrete class (C), the SG between adjacent structures decreases. The percentage of decrease for SG is calculated to decrease with the increase of the concrete class.

Table 5** Calculation for Separation Gap of the similar study **(Saxena, Ghosh, & Debbarma, 2019)



Building Combination	G	Z	SH (m)	N1	N2	S_{ABS} (mm)	S_{SRSS} (mm)	$S_{R*(\Delta 1+\Delta 2)}$ (mm)	S_{max} (mm)
1	20	0.36	3.0	6	8	63.40	45.07	317.00	720.0
2	20	0.36	3.0	10	6	65.90	47.04	329.50	720.0
3	20	0.36	3.0	8	10	86.50	61.38	432.50	960.0
4	25	0.36	3.0	6	8	60.00	42.65	300.00	720.0
5	25	0.36	3.0	10	6	62.40	44.54	312.00	720.0
6	25	0.36	3.0	8	10	81.80	58.05	409.00	960.0
7	30	0.36	3.0	6	8	57.30	40.73	286.50	720.0
8	30	0.36	3.0	10	6	59.60	42.54	298.00	720.0
9	30	0.36	3.0	8	10	78.20	55.49	391.00	960.0
10	35	0.36	3.0	6	8	55.10	39.17	275.50	720.0
11	35	0.36	3.0	10	6	57.30	40.90	286.50	720.0
12	35	0.36	3.0	8	10	75.20	53.37	376.00	960.0
13	40	0.36	3.0	6	8	53.30	37.89	266.50	720.0
14	40	0.36	3.0	10	6	55.50	39.62	277.50	720.0
15	40	0.36	3.0	8	10	72.80	51.66	364.00	960.0
16	30	0.36	3.0	6	8	57.30	40.73	286.50	720.0
17	30	0.36	3.0	10	6	59.60	42.54	298.00	720.0
18	30	0.36	3.0	8	10	78.20	55.49	391.00	960.0
19	30	0.24	3.0	6	8	38.20	27.16	191.00	720.0
20	30	0.24	3.0	10	6	39.70	28.34	198.50	720.0
21	30	0.24	3.0	8	10	52.10	36.98	260.50	960.0
22	30	0.16	3.0	6	8	25.40	18.05	127.00	720.0
23	30	0.16	3.0	10	6	26.50	18.92	132.50	720.0
24	30	0.16	3.0	8	10	34.70	24.62	173.50	960.0
25	30	0.1	3.0	6	8	15.90	11.31	79.50	720.0
26	30	0.1	3.0	10	6	16.50	11.78	82.50	720.0
27	30	0.1	3.0	8	10	21.70	15.40	108.50	960.0
28	30	0.36	2.8	6	8	51.20	36.39	2560	672.0
29	30	0.36	2.8	10	6	53.30	38.04	266.50	672.0
30	30	0.36	2.8	8	10	69.90	49.60	349.50	896.0
31	30	0.36	3.0	6	8	57.30	40.73	286.50	720.0
32	30	0.36	3.0	10	6	59.60	42.54	298.00	720.0
33	30	0.36	3.0	8	10	78.20	55.49	391.00	960.0
34	30	0.36	3.2	6	8	63.60	45.21	318.00	768.0
35	30	0.36	3.2	10	6	66.20	47.26	331.00	768.0
36	30	0.36	3.2	8	10	86.80	61.60	434.00	1024.0
37	30	0.36	3.5	6	8	73.70	52.40	368.50	840.0
38	30	0.36	3.5	10	6	76.80	54.84	384.00	840.0
39	30	0.36	3.5	8	10	100.70	71.47	503.5	1120.0
40	30	0.36	4.0	6	8	92.20	65.56	461.00	960.0
41	30	0.36	4.0	10	6	96.00	68.56	480.00	960.0
42	30	0.36	4.0	8	10	126.10	89.50	630.50	1280.0

Meanwhile, in the case number two it is observed that with the increase of the zone factor, the SG gets larger. For the increase of zone factor from 0.15 to 0.20, the percentage increase is 31.5%, for the increase from 0.20 to 0.25, the percentage increase is 25.5 % and for the increase from 0.25 to 0.30, the percentage increase is 21.2%. For the case number three, where the variable is the change of storey level, it is observed that with the increase of storey height, the lateral displacements of the structures increase. With the increase of storey height from 2.8m to 3.0m, the SG increases by 21.7% and with the increase of storey height from 3.0m to 3.5m, the SG increases by 18.5%. So, since a similar changing tendency for SG is occurring as in the other study, this means that this evaluating process is effective for this study. Both studies have differences in numerical values for SG due to several reasons, including here: difference in number of storeys for buildings (in the study of Saxena et al. buildings were 6, 8 and 10 storey, while in this study buildings were 7 and 11 storey), difference in seismic zone factors, concrete grades and in storey heights.

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

Since the urbanization rate is increasing day by day, the available land is very limited and this results in higher costs of land and closely built structures. In order to avoid the seismic pounding, which is a serious issue during an earthquake, a solution for such problem is the provision of a safe separation gap between adjacent structures. For that reason, the main attention of the work has been to evaluate the minimum separation gap which provides enough security and safety during seismic vibrations of adjacent structures.

- It has been noticed that in most of the studies and codal provisions, SG is evaluated based on the overall elevation of buildings, meanwhile this study gives an emphasis in the influence of other parameters such as concrete class, seismic zone factor and storey height. By analysing these parameters in the buildings, it is concluded that with their variation, the SG changes as well.
- All results presented in this study are derived from linear static analysis performed on regular two dimensional RC frame structures.
- It can be noticed that by increasing the concrete class (C), the SG between adjacent structures decreases. The percentage of decrease for SG is calculated to decrease with the increase of the concrete class (0.94% and 0.45%). Eventhough providing a higher concrete class will reduce the spacing of separation gap, for construction companies this approach might increase the total cost of the project, which is not convenient, especially for Albanian practices. Beside this, considering the amount of percentage change, the difference of the SG is not very significant.
- For the increase of zone factor from 0.15 to 0.20, the percentage increase is 31.5%, for the increase from 0.20 to 0.25, the percentage

increase is 25.5 % and for the increase from 0.25 to 0.30, the percentage increase is 21.2%. With the increase of storey height from 2.8m to 3.0m, the SG increases by 21.7% and with the increase of storey height from 3.0m to 3.5m, the SG increases by 18.5%.

- The required SG calculated by using IS1893, 2016 provision $S_{q*(ui+uj)}$ and FEMA 356 maximum SG S_{max} overestimate the required SG, which is not convenient for land usage and cost.
- The closest building combination for the current existing set of buildings is the combination 2. Since the existent buildings are designed and constructed based on Eurocodes, the SG of the adjacent buildings is calculated using SRSS method. For building combination 2, according to SRSS method, the SG is 8.896947cm. The current separation joint between the structures is 10 cm. This means that the model results are in consonance with the real provided gap.
- The KTP-89 provision from Albanian Seismic Design Code requires a minimum separation gap that is larger than Eurocode minimum separation gap required. From the safety perspective we can say that the Albanian practice provides a safer seismic joint, but from the economic perspective we would say that it is more costly to implement it due to high price of land usage.

5.2 Recommendations for future research

This study was focused only on reinforced concrete, mid-rise buildings designed by Eurocodes, meanwhile in Albania most of the buildings are constructed using old Albanian codal practice or without any code. For an accurate estimation of SG between adjacent buildings in Albanian practice, further studies should include in investigation different types of structure.

Buildings are assumed as symmetrical in plan and structural irregularities are not included. Further investigations can be done taking into consideration asymmetrical structures with irregularities and non-linear analysis can be performed for more realistic results.

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