Structural Joints Influence on the Seismic Behavior of an Irregular Residential Building in Lisbon

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Abstract: This case study focuses on the influence that the adoption of structural joints has on the seismic behavior of an irregular plant building. This study concerns a residential building, irregular in plant, located in Lisbon. The work begins with an analysis of the building's architectural design and subsequent preliminary design of the main structural elements. The quantification of actions and security checks follow the principles and recommendations in the Eurocodes. To understand the influence of structural joints in the seismic behavior of the building it is necessary to study two structures: the building with the joints and the same building without the joints. For each structure the seismic behavior is analyzed and then the main structural elements are dimensioned. The location of the joints is very important as it affects the behavior of the entire building. Three-dimensional modeling of the building and calculation of seismic effects it´s done with SAP2000 program. The rebar calculation of the main structural elements it´s done with the support of the XD-CoSec program. The independent buildings resulting from the adoption of joints are more regular. This allows to admit higher energy dissipation capacity which leads to lower seismic efforts. However it is necessary to provide the structural elements of plastic deformation capacity, or ductility. The work concludes with the comparison of results in terms of seismic effects on the structure and reinforcement ratios in the main structural elements.

Keywords: Structural joints, Structural regularity, design, confinement, Eurocode, SAP2000

1. INTRODUCTION

Nowadays, space restrictions and increased complexity of the architectural designs lead, in many cases, to the implementation of irregular structures.

This case study focuses on the influence that the adoption of structural joints has on the seismic behavior of a reinforced concrete building. This study concerns a residential building, irregular in plan, located in Lisbon.

Starting with the analysis of the architectural drawings, the different stages of a structural project are covered. To understand the influence of structural joints in the seismic behavior of the building it is necessary to study two structures: the building with joints and the same building without joints. The joints will turn the irregular building in three regular ones.

The referred building is a seven-storey building with two underground floors. The two basement floor have 1551 m^2 and the elevated floors have 979 m^2.

The quantification of actions and security checks follow the principles and recommendations in the Eurocodes. Three-dimensional modeling of the building and calculation of seismic effects was done with SAP2000 program. The design of the vertical main structural elements was done with the support of XD-CoSec program.

2. Design Criteria

The concrete used in the project was specified according to the environmental exposure of the structural elements referred in table 1 and the steel grade was A500 NR SD.

Table 1 – Concrete specification, *NP EN206-1*

Element	Specification	Rebar cover
Containment walls	C25/30, XC2, CL 0.4, $D_{máx}$ 25, S3	40 mm
Direct foundations	C25/30, XC2, CL 0.4, $D_{máx}$ 25, S3	50 mm
Slab	C30/37, XC1, CL 0.4, $D_{máx}$ 25, S3	25 mm
Columns and walls	C30/37, XC1, CL 0.4, $D_{máx}$ 25, S3	35 mm

Throughout the building´s lifespan the structure is subjected to permanent actions as well as variable actions. These were defined and quantified according to *EN1991-1-1*. The combination of actions followed the recommendations in *EN1990*.

Table 2 - Permanent actions, *Tabelas Diversas (IST)*

Zone	Description	G [kN/m^2]
Terrace	Coatings terraces, including concrete shape layer, and protections.	2,0
Living area	Usual floor coverings	1,5
Garden	30 cm of soil	5,0
Garage	Thin covering layer	1,5
Stairs	Usual floor coverings	2,0

Table 3 - Variable actions, *EN1991-1-1*

Element	EC1	Description	Q_k [kN/m^2]
Terrace	I	Accessible terrace for domestic and residential activities	2,0
Living area	A	Domestic and residential activities	2,0
Garage	F	Car parking	2,5
Stairs	A	Passage areas	3,0

In Portugal the seismic action has an important role in structural designs. Its effects are quantified in EC8 which considers two different seismic actions: type I (distant epicenter) and type II (close epicenter). Both seismic actions are quantified trough the definition of a response spectrum that has into account the location of the building and the geotechnical conditions of its foundations.

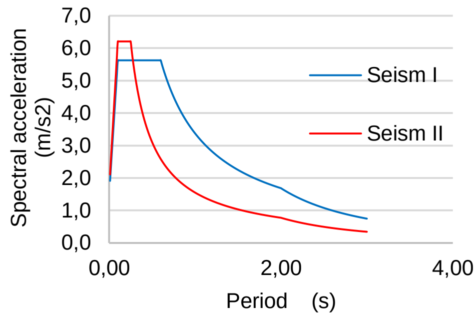

Figure 1 - Horizontal elastic response spectrum

3. Structural Joints

The EC8 recommends that buildings structures should have a dissipative and ductile behavior in order to avoid brittle failure mechanisms. Therefore, structures should be simple and regular. To follow this recommendation structural joints can be used to divide an irregular building into independent dynamic blocks that are more regular.

These blocks must have an appropriate distance between them in order to avoid clash.

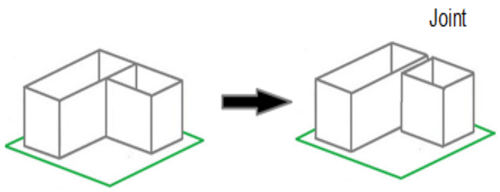

Figure 2 - Illustration of the structural joint position

According to *EN1998-1*, the distance between blocks must be at least: $\Delta = \sqrt{d_1^2 + d_2^2}$. This distance can be reduce in 30% if the floors are at the same level.

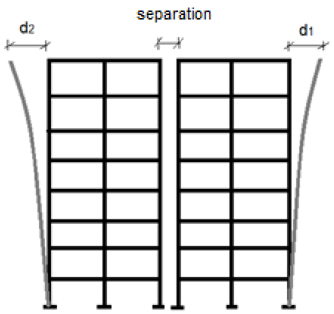

Figure 3 - Separation distance

4. Pre-design

The pre-design is a very important stage because it´s a way to obtain a first approximation of the main structural elements. For the pre-design of the flat slab thickness, it was considered the following expression: $e \approx L_{máx}/(25\ to\ 30)$, suggested by *Appleton e Marchão (2012)*. It is possible to identify two different regions in the building. The zone 1 has a span of 6,5 m while zone 2 has a bigger span – 7,7 m. Therefore in zone 1 was adopted a flat slab with 23 cm thickness while in zone 2 was adopted 27 cm.

After deciding the flat slab thickness there were made three specific verifications:

- Reduced bending moment limitation according to *Appleton e Marchão (2012)*: $\mu^+ \leq 0{,}18$ and $\mu^- \leq 0{,}30$;
- Punching shear verification;
- Slab deformation verification *Appleton e Marchão (2009)*;

For the pre-design of the beams it was defined a width of 0,30 m. The height was estimated with the following expression: $h \approx \frac{L_{máx}}{10\ to\ 12}$ according to *Appleton J. (2013)*. Therefore were defined two beam sections: V1 has a height of 0,55 m while V2 has 0,65 m.

The pre-design of the columns sections was made according to *Appleton J. (2013)*:

$$\sigma'_c = \frac{N_{sd}}{A_{pilar}} \leq (0{,}8\ a\ 1{,}0).fcd$$

The calculation of the compression force in each column was made with SAP2000 software.

The result of the columns pre-design is displayed in table 4.

Table 4 - Columns pre-design

Section [cm]	Column
30 x 40	P23, P24, P31; P52, P53, P54
35 x 50	P4, P6, P7, P9, P10, P12 to P16, P18 to P22, P25, P28 to P32, P35 to P40, P43 to P50
50 x 65	P5, P8 and P11
35 x 80	P1, P2, P3, P17, P26, P27, P33, P34, P41, P42, P51

The shear walls were defined following the architectural drawings. Their thickness was set on 0,25 m, according to EC8 recommendation.

Finally, the direct foundations for the building were pre-design so that the tension in soil did not exceed 400 kPa.

5. Modeling of the building

The three-dimensional modeling of the building was made in SAP2000 software. The mechanical characteristics of the materials were inserted in the code.

The beams and columns were modeled through frame elements. Their torsional stiffness was despised.

Shear walls were modeled using frame elements. To simulate the connection and compatibility between the walls and the slabs it was used a very rigid frame.

In order to model the flat slabs, it was used thick shell elements. Their torsional stiffness was also despised.

The columns foundations were simulated through the restriction of all displacements and rotations. The foundations of the shear walls have the displacements restricted but their rotations are allowed and have associated a stiffness calculated according to *Oliveira Pedro, J. (IST)*.

In order to achieve a correct modeling of the structural joints, all the nodes were separated along the joint. The beams and columns that were located along the joint were duplicated. The vibrations modes of the structure ensured that the joints were correctly modeled.

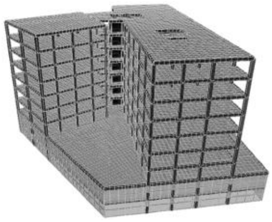

Figure 4 – SAP2000 finite element model

6. Seismic Analysis

In order to perform a complete seismic analysis of the whole building, as well as the resultant blocks due to the introduction of joints, was used SAP2000 software.

The determination of the seismic effects was based on a modal response spectrum analysis.

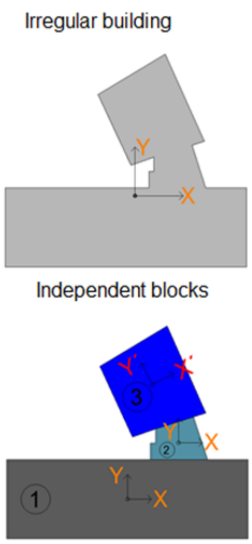

Figure 5 - Designation of the independent blocks

Table 5 - Oscillating mass of each structure

Structure	Oscillating mass [ton]	$M_{o,i}/M_{Total}$ [%]
Block 1	7309.2	54,6%
Block 2	810,0	6,1%
Block 3	2801,7	20,9%
Original building	10706,0	80,0%

In table 5 it´s indicated the oscillating mass of each structure. Because of the basement floors, the oscillating mass of the original building represents 80% of the total mass.

EC8 recommends the consideration of all vibrations modes until they sum up 90% of the oscillating mass. In figure 6 is displayed the oscillating frequencies of the original building as well as the independent blocks.

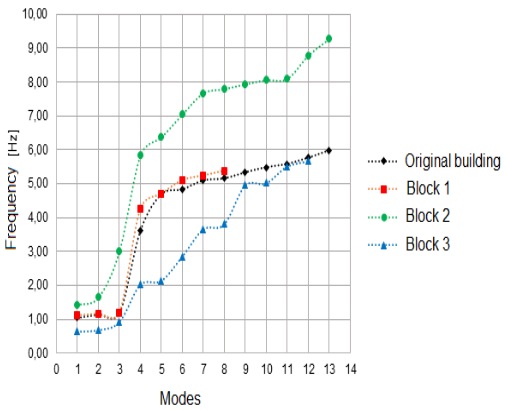

Figure 6 - Vibration Modes Frequencies

Table 6 - Main vibration modes

Modes	Original Building	Blocks 1	Blocks 2	Blocks 3
1	Transl. X + torsion	Transl. X	Transl. Y	Transl. X´
2	Transl. Y + torsion	Transl. Y	Transl. X	Transl. Y´
3	Torsion	Torsion	Torsion	Torsion
4	Torsion	Torsion	Transl. Y	Transl. X´
5	Torsion	Transl. Z	Transl. Z	Transl. Y´
6	Torsion	Transl. X + Z	Transl. X + Z	Torsion
7	Transl. Z	Transl. Z	-	Transl. X´
8	Transl. Z	Transl. Y + Z	-	Transl. Y´
9	Transl. Z + torsion	-*	-	Transl. Z´
10	Transl. Z	-	-	Torsion
11	Transl. Z	-	-	Transl. X´
12	Transl. X+Y	-	-	Transl. X´+Y´

* Modes that weren´t analyzed because it was already reached 90% of oscillating mass, or, in case of block 2, were inflections of translations in Z direction;

From figure 6 we can conclude that block 1 and the original building have very similar frequencies. That´s because block 1 is the biggest of the three blocks. We can also notice that block 3 has the most flexible behavior while block 2 is the most rigid.

In table 6 it´s described the vibration modes of the structures. The original building is flexible to torsion, as its first modes are torsion. The independent blocks have a more regular behavior.

The classification of buildings as regular or irregular influences the structural model adopted in the analysis and also the behavior factor *q*.

In this study case it is necessary to classify the original building and the three blocks that result from the introduction of structural joints. In table 7 it´s shown whether the structures comply or not with the regularity criteria indicated in *EN1998-1*.

Table 7 – EC8 regularity in plan criteria

Criteria	Original building	Blocks 1	Blocks 2	Blocks 3
Mass and stiffness symmetric distribution	X	✓	X	✓
Compact shape in plan	X	✓	✓	✓
Floor diaphragm behavior	✓	✓	✓	✓
Orthogonal dimensions relation < 4	X	✓	✓	✓
$e_{0i} \leq 0{,}30\ r_i$	✓	✓	X	✓
$r_i \geq l_s$	X	✓	✓	✓

From table 7 we can deduce that the independent blocks have a more regular behavior in plan. The original building is classified as flexible to torsion. Block 1 and 3 are regular in plan and block 2 is not.

As regards the regularity in elevation, all the buildings in study are considered regular.

In order to define an adequate behavior factor, each structural system must be classified according to *EN1998-1*:

Table 8 - Structural system classification

Structure		**Classification**
Original building		Torsionally flexible system
Building with joints	Block 1	Wall-equivalent dual system
	Block 2	Wall system
	Block 3	Frame system

Therefore, each structure has a different behavior factor.

Table 9 - Behavior factors

Structure		q	
		Direction X	Direction Y
Original building		2,0	2,0
Building with joints	Block 1	3,6	3,6
	Block 2	3,0	3,0
	Block 3	3,9	3,9

By looking at table 9 we can see that the independent blocks have higher behavior factors. This reflects their higher capacity in terms of dissipating seismic energy.

The seismic action was modeled in SAP2000. The seismic action type I was the most conditioning. The seismic coefficient β was calculated for each structure by:

$$\beta = \frac{F_B}{F_g}.$$

where, F_g refers to the structure weight while F_b to the horizontal base reaction due to the seismic action.

Table 10 - Seismic coefficients

Structure	Seismic action type I	
	Direction X	Direction Y
Original building	0,124	0,151
Block 1	0,078	0,085
Block 2	0,127	0,112
Block 3	0,042	0,043

From table 10 it´s noticeable that the independent blocks have lower seismic coefficients than the original building. This improvement is explained by the fact that these blocks have higher behavior factors. Block 2 maintains a high seismic coefficient. This happens because his modes are associated to the high values of the response spectrum.

According to *EN1998-1* it was considered a torsional moment in each floor of the structures to take into account the uncertainty of mass locations.
EC8 establishes limits for the interstorey drift. This limits are intended to ensure damage limitation as well as verify if there is the need to consider second-order effects. All structures verified the interstorey limits. The original building, block 1 and block 2 didn´t need to take into account the second-order effects. Block 3, as the most flexible of the structures in study, was considered sensible to second-order effects. To take this into account, the seismic effects were increased in 20%.

Through the study of the structures deformed shape due to the seismic action, it was calculated the joints dimensions.

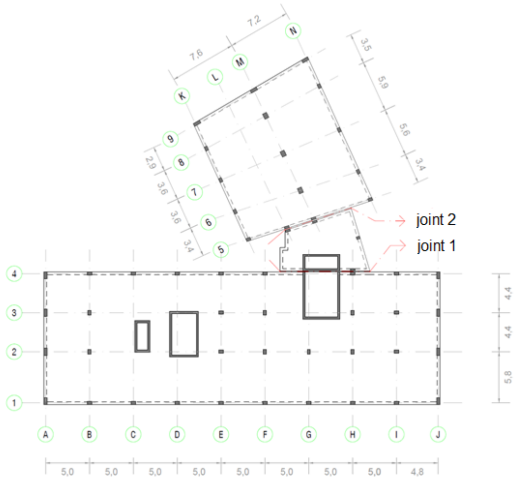

Figure 7 – Joint's location

According to EC8 the distance between blocks must be superior to the square root of sum of squares of the maximum blocks displacements. As the block´s floors are at the same level this distance can be reduced in 30%. In table 11 it´s shown the obtained values for joint 1 and 2:

Table 11 - Joint's dimensions

Structural joint 1			
$d_{block\ 1}$ [cm]	$d_{block\ 2}$ [cm]	Δ [cm]	70% Δ [cm]
9,5	4,7	10,6	7,4

Structural joint 2			
$d_{block\ 2}$ [cm]	$d_{block\ 3}$ [cm]	Δ [cm]	70% Δ [cm]
11,2	13,2	17,3	12,1

From observation of the deformed shape of each structure it was a noticeable a relation between the EC8 structural system classification, described in table 8, and the respective deformed shape in elevation. From figure 8 we can see that block 3, as a frame system, has the displacements between floors decreasing in height. In contrast, block 2, as a wall system, has the displacements between floor increasing in height.

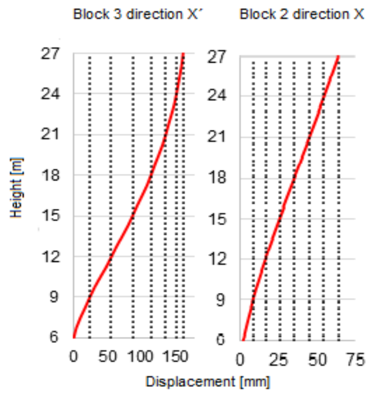

Figure 8 - Deformed Shape

The original building, integrates this two different behaviors because the slab connects both systems. Therefore, the displacements between floors are relatively the same in height, which shows that dual systems are efficient in terms of controlling seismic displacements, *LOPES, M. et. al. (2008)*.

7. Design

After the seismic analysis of each structure, the vertical main structural elements were designed in order to observe the influence of the adoption of joint in the required rebar.

Starting with the beams, it was take into account the forces due to the seismic combination of action.

The rebar calculation followed the *EN1992-1-1* and *EN1998-1* recommendations.

Then it was compared each beam section of the original building with the analogous beam section of the independent blocks. It was concluded that the introduction of joints lead to an average reduction of 18% in the design bending moment of the beams.

After calculating the required rebar in each section it was concluded that reinforcement ratio was reduced in 30%.

Following the principles of capacity design it was considered that plastic bearings could only occur in the beams and not in the columns. Therefore the resistant bending moment of the columns must be superior to the beams.

The design of the columns was done using the XD-CoSec code and according to the principles in *EN1992-1-1* and *EN1998-1*. For the longitudinal reinforcement ratio it was concluded that the introduction of joints caused an average reduction of 14%. As regards to transversal reinforcement, the design shear forces were reduced with the introduction of joints. However, in terms of confinement reinforcement in the critical zone, it was verified that the independent blocks were much more demanding. To measure this increase in required confinement reinforcement it was calculated the mechanic volumetric ratio of stirrups, W_{wd} that was needed to comply with the EC8 confinement requirements. This parameter was calculated to all the analyzed columns of the original building and the analogous ones in the independent blocks. It was concluded that the mechanic volumetric ratio of stirrups needed to achieve confinement increased, in average, 150% after the introduction of joints.

Therefore the transversal reinforcement of the columns increased with the introduction of joints.

Finally the shear walls were analyzed. The introduction of structural joints significantly reduced the seismic forces. In average, the shear forces were reduced in 44% and the bending moment in 63%. This reductions are plausible because, when separating the building into blocks, the walls are less solicited. As regards to transversal reinforcement, the reduction in shear force lead to less adopted reinforcement. In terms of confinement reinforcement it was verified that the independent blocks were more demanding, similarly as what happened with the columns.

8. Conclusion

This work was very useful as it put into practice many concepts learned during the course. The main objectives of the thesis were reached. After a pre-design of the main structural elements, a complete seismic analysis was performed to the original building and to the independent blocks that resulted from the introduction of structural joints.

For a good structural concept, buildings should be regular and symmetric, *APPLETON, J. (1988).*

Therefore, the joint’s location was chosen in order to turn the original building, with a *L* shape, into three regular buildings.

The modal analysis of each structure showed that the original building was flexible to torsion. The three independent block had a more regular behavior, as their first modes corresponded to translations.

According to the recommendations of EC8, the independent blocks have higher behavior factors associated.

As each independent block has a behavior factor, it was necessary to build a finite element model for each structure.

It was expected the seismic effects would be reduced after the introduction of joints. That happened to block 1 and 3, but not to block 2. This happened because his modes are associated to the high values of the response spectrum, the interval between T_B and T_C.

The distribution of vertical elements is very important. They influence the stiffness, and therefore the frequencies of the vibrating modes, of the independent blocks.

Based on the study that was made, we can conclude the adoption of seismic joints in an irregular building does not necessarily reduce the seismic action effects in the independent blocks. In order to achieve an efficient use of seismic joints, two aspects must be previously analyzed:

- The independent block should be more regular in plan and in elevation and therefore be associated to higher behavior factors;
- The frequencies of the main vibrating modes of the independent block should not be associated to the high values of the response spectrum;

In average, the reduction of the seismic effects in the independent blocks, resulted in a reduction of the required longitudinal reinforcement of the main vertical elements. In terms of transversal reinforcement it was verified that the higher behavior factors conduced to higher confinement requirements, according to EC8.

The columns confinement is very important and was carefully analyzed.

By having the concrete well confined it is possible to achieve higher extensions which allows the steel to also have higher deformations, *Monteiro Vítor E. Cansado Carvalho (IST)*.

This promotes the global ductility of the structure.

Table 12 - Conclusion

Original building	
⇓	
Irregular	
⇓	
Lower capacity of energy dissipation	
⇓	
Lower behavior factor	
⇓	⇓
Higher seismic effects	Lower confinement requirements

Independent blocks	
⇓	
Regular	
⇓	
Higher capacity of energy dissipation	
⇓	
Higher behavior factor	
⇓	⇓
Lower seismic effects	Higher confinement requirements

In short, this work contributed to explore the advantages and disadvantages of adopting seismic joints in order to turn an irregular building into independent blocks that are regular in plan.

The reduction in reinforcement may be appealing in economic terms. However the adoption of joints in a building have some constructive issues associated with, such as water infiltrations and thermal bridges.

As a structural engineer, each solution must be studied and analyzed, so that the durability and safety of the structure is ensured.

9. References

[1] **EN 1990** - Eurocódigo 0 - *Bases Para o Projecto de Estruturas*. 2009.

[2] **APPLETON, J. (2013)** - *Estruturas de betão Vol. 1*. 1ª Ed. Lisboa: Orion.

[3] **EN 1992-1-1** - Eurocódigo 2 - *Projecto de Estruturas de Betão - Parte 1-1: Regras Gerais e Regras para Edifícios*. 2010.

[4] **Grupo de Betão Armado e pré-esforçado** - *Tabelas Diversas*. Instituto Superior Técnico – Estruturas de Edifícios.

[5] **EN 1991-1-1** - Eurocódigo 1 - *Ações em Estruturas - Parte 1-1: Ações Gerais*. 2009.

[6] **EN 1998-1** - Eurocódigo 8 - *Projecto de Estruturas para Resistência aos Sismos - Parte 1: Regras Gerais, Ações Sísmicas e Regras para Edifícios.* 2010.

[7] **Appleton e Marchão (2012)** - *Folhas de apoio às Aulas de Estruturas de Betão II.* Instituto Superior Técnico.

[8] **Appleton e Marchão (2009)** - *Folhas de apoio às Aulas de Estruturas de Betão I.* Instituto Superior Técnico.

[9] **OLIVEIRA PEDRO, José** - *Modelação de Fundações na Análise Estrutural.* Instituto Superior técnico - Estruturas Especiais.

[10] **Lopes, M., & et al. (2008).** - *Sismos e Edifícios.* 1ª Ed., Lisboa: Orion.

[11] **APPLETON, J. (2013)** - *Estruturas de Betão Vol. 2.* 1ª Ed. Lisboa: Orion, 2013.

[12] **NP EN 206 - 1** - *Especificação, desempenho, produção e conformidade*. 2007.

[13] **Eliud Hernández (2009)** – *Manual de Aplicación del Programa SAP2000 v14*.

[14] **APPLETON, J. (1988)** – *Concepção e Projecto de Estruturas de Edifícios*. IST.

[15] **Monteiro Vítor E. Cansado Carvalho** – *Comportamento de Elementos de Betão Armado sujeitos a ações repetidas e alternadas.* IST.