Initial conceptual design of earthquake resistant r/c and masonry buildings according to Eurocode 8

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Abstract

This paper summarizes and analyses the basic requirements associated with the initial conceptual design of reinforced concrete and masonry buildings that are included in Eurocode 8 (EC8) into an easily understandable synopsis accompanied with practical examples and pictures. The synopsis is intended to be used by architects and other types of engineers; its purpose is to increase the knowledge about the rules of earthquake resistant design, especially about those that should be respected during the initial conceptual design of the building. In this way we can approach the problem of constructing an earthquake resistant structure from another end, by trying to avoid the “bad” structure layouts during the initial design phase.

1 Introduction

The experiences from the past strong earthquakes prove that the initial conceptual design of a building is extremely important for the behaviour of the building during an earthquake. It was shown repeatedly that no static analysis can assure a good dissipation of energy and favourable distribution of damage in irregular buildings, such as, for example, structures with large asymmetry or distinctively soft storeys. The responsibility for a “good” initial conceptual design lies with the architect, as well as with the structural engineer providing numerical proof of the structure’s safety. The guidelines for a “good” conceptual design are included in building codes, however, the codes are much more suited to the needs of structural engineers as to the needs of architects. This can be seen also in recent EC8, where many requirements related to initial design include formulae with parameters that could be obtained only by preliminary static
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analysis. On the other hand, same requirements are formulated only as recommendations and their fulfilment depends on experience and judgment of the designer. From this point of view the cooperation between architect and structural engineer would be therefore necessary also during the initial phase of the design of the building. In practice it is difficult to perform static analysis if, for example, the floor plan is still under discussion, so this cooperation is not working properly in many cases (especially for less complex buildings).

It is evident that architects should be familiar with the basic rules of earthquake resistant design, so that they can be incorporated in their building solution already from the first sketch. The present paper summarizes and analyses the requirements associated with initial conceptual design that is included in EC8 into an easily understandable synopsis accompanied with practical examples.

2 Architect, constructor and initial building design

The initial building design is usually proposed by an architect who should harmonize the needs of investor with his own ideas and concepts, as well as with all static and other technologic requirements. It is also necessary to adapt the functionality of the building, to define the major dimensions of the building and to propose the arrangement of the rooms in the way that correspond best to the given location, as well as to the needs of the investor and/or user. Of course the architect also tends to design a recognizable structure and strives to fulfil the architectural, urban and artistic criteria. On this basis the outline scheme of the building is usually selected. Many times at that point the structure is already well defined and often also confirmed by the investor. The structural analysis, that follows, might reveal some mistakes and in this case it is necessary to correct the project. This phase causes many contradictions between architectural and structural field. Conflicts start in most cases between the architect, who does not have enough knowledge about construction, and the civil engineer who does not have the understanding of complexity of the architect’s work and his artistic mission when designing a building and site. In the usual practice nowadays it seems that the choice of the structure layout is left to the architect and the proof of its safety is left exclusively to the structural engineer. This approach is ineffective and should be treated as old-fashioned. More and more complex and pretentious architectural creations that we are witnessing today demand a dynamic cooperation among architects and engineers from all fields. We hope the presented synopsis will – at least to some extend – help to overcome the extensive problem of so needed mutual cooperation.

3 The philosophy of the structural design on seismic areas

The destroying power of the energy brought in a structure by an earthquake is enormous. Due to economic reasons most of the structures cannot be made strong enough to accommodate all of that energy without any plastic deformations (i.e. damage). Depending on the structure and its life cycle, a certain damage of the structure therefore must be tolerated. For this reason the
actual (elastic) seismic forces are reduced to design forces by behaviour factor $q$. The adopted reduction factors are valid for the structures with reasonable regularity in plan and elevation. We should be aware that during a real earthquake, the forces could be much larger than the design forces (up to 6 times) so all numerical proofs based on reduced forces and elastic analysis cannot warrant the favourable behaviour during a strong earthquake.

According to EC8, a structural designer can choose between three ductility classes. Ductility class defines balance between allowed reduction of seismic load and the complexity of structural design and realization of details. These ductility classes are low (DC/Low), medium (DC/Medium) and high (DC/High). Low ductility class prescribes larger calculated seismic forces in combination with less complicated realization of details, whereas the high ductility class prescribes reduced earthquake forces in combination with high-quality realization of details and the use of more accurate calculating methods.

4 Synopsis of basic code requirements related to initial conceptual design (abstract from EC8)

Because of the limited length of the article only the most important requirements are briefly summarized.

Purpose
The main purpose of EC8 provisions in case of an earthquake is to protect human lives, reduce material damage and ensure that important buildings remain useful also after an earthquake.

Basic requirements

*No collapse requirement:* The structure should be designed and constructed to withstand the seismic action without local or global collapse, thus retaining its structural integrity and a residual load bearing capacity after the seismic events.

*Damage limitation requirement:* This criteria demands that the structure withstand an earthquake without the occurrence of damage and the associated limitations of use, the costs of which would be disproportionately high in comparison with the costs of the structure itself.

*Global stability requirement:* The stability of the entire structure against collapse and slide also has to be examined. It also has to be examined whether the foundations and ground have the capacity of withstanding the shocks of an earthquake without suffering major permanent deformations.

4.1 Basic requirements for buildings

Structure regularity
The guiding principles governing the initial conceptual design are as follows:
a) The aspect of seismic hazard should be taken into account in the early stages of the conceptual design of a building,b) Structure should be simple,c) Transmission of the seismic (inertia) forces to the ground should be direct and clear (figure 1a),
d) Uniformity, symmetry and redundancy should be ensured,

e) Structure should be statically undetermined,

f) Bi-directional resistance and stiffness should be ensured (*figure 1b*),

g) Torsion resistance and stiffness should be ensured (main structural elements should be placed symmetrically nearby periphery of the building) (*figure 1c*),

h) Structural elements should be appropriately connected with floor systems or diaphragms (which have to have sufficient in-plane stiffness),

i) Building should have adequate foundation.

![Diagrams](image1)

**Figure 1:** Examples of regular and irregular initial building designs:
a): Uniformity along the height; b): Bi-directional resistance and stiffness; c): Symmetry in plan.

**The regularity criteria in plan and in elevation**

The regularity of the structure in the plan of different floors, as well as in elevation of the building should be ensured. The regularity criteria in plan are:

a) With respect to the lateral stiffness and mass distribution, the position of force resisting elements should be approximately symmetrical in plan with respect to two orthogonal axes (*Figure 2*).

![Diagrams](image2)

**Figure 2:** Regularity of a building in plan and appropriate position of force resisting elements.

b) The plan configuration should be compact. The dimensions of recesses in one direction should not exceed 25% of the whole dimension of floor area in this direction (compact plan configuration which is not H, L, I, C or X - shaped).

c) The in-plane stiffness of the floors should be sufficiently large in comparison with the lateral stiffness of the vertical structural elements, so that the deformation of the floor has a small effect on the distribution of the forces among the vertical structural elements.
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Figure 3: Regularity of initial building design in plan according to distribution of masses and subdivision of the entire building by seismic joints.

The regularity criteria in elevation are as follows:

a) All lateral load-resisting systems, like cores, structural walls or frames should run without interruption from the foundations to the top of the building.

b) The deflected shapes of the individual systems under horizontal loads should not be very different. This condition may be considered satisfied in case of frame systems and wall systems.

c) Both the lateral stiffness and the mass of the individual storeys should remain constant or reduce gradually, without abrupt changes, from the base to the top (Figure 4).

Figure 4: Large eccentricities and uniformity along the height and influence of different heights of columns.

d) When set-backs are present, the following additional conditions apply:
Structure is regular if set-back at any floor is not greater than 20% of the dimension of the plan below. If the set-back does not preserve symmetry, in each face, the sum of the set-backs at all storeys should not exceed than 30% of the plan dimension of the first storey, and the individual set-backs should not exceed 10% of the dimension of the plan below (Figure 5).

Figure 5: Regularity of set-backs.

Other irregularities:
Longer overhanging elements should be avoided. Columns should run directly to the ground where this is possible. Supporting columns with beams is not recommendable. Initial structure design should follow the above recommendations. If necessary, uniformity may be realized by subdividing the
entire building by seismic joints into dynamically independent units, provided that these joints are designed against pounding of the individual units (Figure 3). The construction of completely irregular structures is not explicitly forbidden, however, it is much harder to ensure a desirable level of safety against strong earthquake for an irregular structure. For this reason the irregular structures are in general less safe, even if the structure is capable to withstand design forces.

Non-structural elements (appendages) of buildings shall be adequately connected to the main structure
Non-structural elements (appendages) of buildings (e.g. parapets, gables antennae, mechanical appendages and equipment, curtain walls, partitions, railings) should be verified to resist the designed seismic action. They should be adequately connected to the main structure.

Non-structural elements (in-fills) can help to dissipate the energy, if they are correctly arranged and connected to the structure. It is necessary to prevent negative influences of individual non-structural elements or partial in-fills, that can damage the main R/C structure (the effect of short column).

4.2 Specific rules for concrete buildings

Material requirements
The use of concrete class lower than C 16/20 (DC/M) or C 20/25 (DC/H) is not allowed in primary seismic elements. Except for stirrups or crossties, only ribbed bars are allowed as reinforcing steel of primary seismic elements.

Dimensions of beams
Beams (DC/High): width of any beam should be at least 20 cm. Beam width \( b \), beam height \( h \) and beam length \( L \) are related by the following expressions: \( h < 2.5 \ b \) (e.g. 20 cm wide beam can be max. 50 cm high) and \( b > L/50 \) (e.g. 10 m long beam can be min. 20 cm wide), otherwise special proof of safety is needed.

Beams (DC/Medium): width of any beam should be at least 20 cm. Height of a beam should not be greater than \( 4 \times b \) (\( b = \text{width of a beam} \)).

Special care shall be given to critical regions of beams
Provisions for an individual ductility class precisely determine the length of the critical region of the beam, to which special care should be given (concentration of stirrups, increased percent of tensional reinforcement, appropriate ratio between lower and upper reinforcement, etc.).

Width of any beam shall correspond to the width of the supporting column
Width of any beam should not exceed two widths of the column that supports it.

Beam shall not be eccentrically connected to the column
Eccentric connection of the axis of the beam to axis of the column should be avoided. Distance between one and the other axis should be maximum 25% of the width of the column (Figure 6).
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Figure 6: Maximum beam width: $B_w = \min(b_c + h_w, 2b_c)$; and beam eccentrically connected to column: $e < \frac{\text{column width}}{4}$.

Columns shall run continuously to the ground - exceptions are permitted
If columns are supported by beams, the following rules apply:
(a) There should be no eccentricity of the column axis relative to that of the beam.
(b) The beam should be supported by at least two direct supports, such as walls or columns.
(c) Such connection of the beam and column should be treated as a critical region.

Global plastic mechanisms shall be ensured
Columns and beams of the frame system have to be constructed in such a way that the damage occurs mainly at the ends of the beams and at the bottoms of the columns in the ground floor. Such mechanism is called global plastic mechanism (Figure 7, a, b and c). Local plastic mechanisms (Figure 7, d, e, f) have to be avoided by adequate planning and reinforcing of beams and columns of the frame. In general, this can be achieved if the columns are designed to be stronger than beams (the principle of "weak beams and strong columns").

Figure 7: Global (a, b, c) and local (d, e, f) plastic mechanisms.
Dimensions of columns
For DC/High the smaller dimension of cross section of the column should not be less than 25 cm or 1/20 of column height. For DC/Medium and DC/Low the smaller dimension of cross section of the column should not be less than 1/20 of column height, except in special cases when additional proof of safety is needed. To approximately estimate the value of column dimensions we recommend the following expression from Slovenian Earthquake Building codes:

\[
\frac{N}{A} \leq 0.25 \cdot MB
\]  

(1)

MB ........ Strength of concrete (MB30 = 3kN/cm²)
N ............ Axial force due to vertical load
A ............ Cross-section of the column [cm²]

Ductile structural walls shall run continuously to the foundation
Reinforced concrete walls should be fully anchored to the foundations or adequate basement walls. Structural walls supported by slabs or beams are not allowed.

Structural walls shall be slender
It is recommended that structural walls are slender (height/width ≥ 2.0). For such walls it is much easier to ensure a ductile behaviour. Wide and low walls give even stronger resistance to horizontal loads, but they need additional bi-diagonal reinforcement (x-shaped), which has to be appropriately anchored in foundations (Figure 8).

If possible, the structural walls shall be connected with beams (coupled walls)
Individual structural walls can be connected with beams (coupled walls). Coupling of walls by means of slabs should not be taken into account, as it is not effective. The coupling beam should be strong enough to withstand shear forces due to horizontal loads (earthquake) through axial force mechanism in coupled walls. It is recommended, that the coupling beam is not longer than three times its height (ratio 1:3). Irregular disposition of openings in the coupled walls should be avoided, as it prevents the formation of axial forces in walls and hence reduces its resistance to horizontal loads. It is recommended, that the beams are reinforced by bi-diagonal reinforcement (Figure 8).

![Figure 8: Coupled wall and bi-diagonal reinforcement of a coupling beam.](image-url)
Thickness of structural walls and confined boundary elements

Wall ends should be additionally reinforced. These confined boundary elements can be hidden in thickness of the wall (Figure 9) or they can be made as columns at the ends of the wall (Figure 10). Minimum thickness of the confined boundary elements should be at least 1/15 of the storey height and greater than 20 cm. The same condition should be fulfilled for minimum thickness of the wall with hidden confined boundary elements. If the wall is connected to another wall (with flange) with thickness of at least 1/15 of storey height and the length of at least 1/5 of storey height, the thickness of the wall could be smaller (min. 15 cm or 1/20 of storey height).

![Figure 9: "Hidden" confined boundary element (two versions of reinforcement).](image)

![Figure 10: Structural walls and confined boundary elements.](image)

Concrete slabs shall have sufficient in-plane stiffness

Concrete diaphragms and slabs should have sufficient in-plane stiffness, to enable the transmission of seismic horizontal forces to the vertical structural elements. Special verification is required (for DC/High and DC/Medium) for slabs with irregular geometry or divided shapes in plan, diaphragms with recesses and re-entrances, irregular and large openings in the diaphragm, irregular distribution of masses and/or stiffnesses (as e.g. in the case of set-backs or off-sets).

4.3 Specific rules for masonry buildings

Types of masonry:
- unreinforced masonry: it is built from masonry units, without being confined. However, horizontal confining elements (concrete beams or steel ties) should be placed in the plane of every floor level, but in any case with a vertical
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spacing not more than 4.0 m. Building of such a masonry construction is not recommended on areas where higher seismic intensity is expected ($a_g \geq 0.30$ g).

- **confined masonry:** it is built from masonry units and confined with vertical and horizontal confining elements, which have to be bonded together and anchored to the elements of the main structural system.

- **reinforced masonry:** it is built from masonry units, whereas whole construction is reinforced. Horizontal and vertical reinforcement has to be placed in the bed joints or in suitable grooves or cavities in the units.

- **special reinforced masonry systems.**

**Materials (masonry units, mortar)**

According to EC8, the minimum strength of masonry units should be $4.0 \text{ N/mm}^2$ normal to the bed face and $2.0 \text{ N/mm}^2$ parallel to the bed face in the plane of the wall. Except in areas of low seismicity ($a_g < 0.05$ g), such joints should be fully filled with mortar. Minimum mortar strength is M5, and M10 in the case of reinforced masonry. Masonry walls, lintels and parapets should be built by the use of classic bricklayer building techniques.

**Shear walls shall be provided in at least two orthogonal directions**

Masonry buildings should be composed of floors and walls, which are connected in two orthogonal horizontal directions and vertically. The connections between the floors and walls should be provided by steel ties or reinforced concrete ring beams.

**Shear walls shall have adequate thickness and slenderness**

Shear wall dimensions should comply with certain geometric requirements listed in Table 1.

**Table 1: Geometric requirements for masonry shear walls according to EC 8.**

<table>
<thead>
<tr>
<th>Masonry type</th>
<th>$t_{ef\min}$</th>
<th>$(h_{ef}/t_{ef})_{max}$</th>
<th>$(l/h)_{min}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unreinforced, with natural stone units</td>
<td>350 mm</td>
<td>9</td>
<td>0,5</td>
</tr>
<tr>
<td>Unreinforced, with manufactured stone units</td>
<td>240 mm</td>
<td>12</td>
<td>0,4</td>
</tr>
<tr>
<td>Unreinforced, with manufactured stone units, in zones of low seismicity</td>
<td>170 mm</td>
<td>15</td>
<td>0,35</td>
</tr>
<tr>
<td>Confined masonry</td>
<td>240 mm</td>
<td>15</td>
<td>0,3</td>
</tr>
<tr>
<td>Reinforced masonry</td>
<td>240 mm</td>
<td>15</td>
<td>no restrictions</td>
</tr>
</tbody>
</table>

$t_{ef}:$ thickness of the wall; $h_{ef}:$ effective height of the wall; $h: $ greater clear height of the openings adjacent to the wall; $l: $ length of the wall

From Table 1 it can be seen, for example, that in the confined masonry building the minimum thickness of the shear walls should be at least 24 cm if the storey height does not exceed 3,60 m ($h_{ef}/t_{ef} \leq 15$, in our case: $360/24 = 15$).
Shear walls and confining elements shall be correctly constructed
Minimum thickness of an unreinforced wall in seismic areas is 24 cm according to Table 1. The horizontal and vertical confining elements should be bound together and anchored to the elements of the main structural system. In order to obtain an effective bond between the confining elements and the masonry, the concrete of the confining elements should be cast after the masonry has been built. The cross-sectional area of horizontal as well as vertical confining elements should not be less than 300 cm$^2$, with a minimum horizontal dimension of 15 cm (dimension of a confining element should be 15/20 cm, and not for e.g. 12/25 cm).

Horizontal confining elements should be placed in the plane of the wall at every floor level. Their vertical spacing should be less than 4.0 m. Vertical confining elements should be placed as follows (Figure 11):

a) at free edges of each structural wall element,
b) at both sides of any wall opening with the area of more than 1.5 m$^2$ (all door openings with dimensions more than 200/75 cm!)
c) within the wall if necessary in order not to exceed a spacing of 5.0 m between the confining elements,
d) at the intersections of structural walls, wherever the confining elements imposed by the above rules are placed farther than 1.5 m away.

![Figure 11: Placement of the vertical confining elements.](image)

Requirements for reinforced masonry
Basic rules for reinforced masonry are as follows:

a) Horizontal and vertical reinforcement should be placed in the bed joints or in suitable grooves (cavities) in the units,
b) Horizontal reinforcing steel bars should have the diameter of at least 4 mm. They should be anchored by bending around the vertical bars at the ends of the wall,
c) Vertical reinforcements with a cross-section of not less than 200 mm$^2$ should be arranged:
   - at both free edges of every wall element,
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- at every wall intersection,
- within the wall, in order not to exceed a spacing of 5.0 m between such reinforcements,

d) Masonry units with recesses should accommodate the reinforcement needed in lintels and parapets,
e) The parapets and lintels should be regularly bonded to the masonry of the adjoining walls and linked to them by horizontal reinforcement.

Reinforced masonry with cast reinforcement behaves similarly to reinforced concrete. However, reinforced masonry built from masonry units (e.g. hollow brick) and with not cast reinforcement in bed joints largely depends on the sort and quality of the masonry units. The amount of reinforcement that is not balanced with the carrying capacity of the masonry wall is usually not economical.

**Seismic analysis and ‘simple masonry buildings’**

Seismic analysis for masonry buildings is necessary in all cases, except for the so called ‘simple masonry buildings’. Simple masonry buildings are, according to EC8, regular, rectangular and mainly symmetrical in plan in two orthogonal directions. Such structures are much more predictable during an earthquake, so a seismic analysis is not deemed necessary. It is not allowed to consider a building as ‘simple masonry building’ in zones of high seismicity ($a_x>0.20$ g).

**5 Conclusions**

The article briefly summarizes EC8 requirements that are important to an architect and should be considered already during initial conceptual building design. The final version of the synopsis is still in progress; in the paper only the most important requirements are presented. It is important to stress that the buildings with extremely unfavourable/unregular floor plan cannot be transformed into a safe design simply with the help of good static calculation. Any safety verified in such a way is only imaginary and can be easily disproved by a first stronger earthquake impact. The authors hope that architects – constructors will find the synopsis helpful when designing/planning earthquake resistant reinforced concrete or masonry structures.

**References**


