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EFFECTIVE ARCHITECTURE-SEISMIC DESIGN INTEGRATION IN TEACHING PRACTICE: ELEMENTARY SCHOOL DESIGN - CASE STUDY

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Abstract

Because of housing the most vulnerable part of any society, the children, and due to the use of school spaces and facilities as post-disaster management centers, the paramount importance of an adequate seismic design of schools is widely recognized. Such adequacy requires nevertheless the combined effort of engineers and architects, whose interests usually seem to be rather confrontational than integrated for the sake of the ultimate building safety. This issue becomes particularly notorious when teaching seismic design principles to students of architecture, as they perceive such principles as a serious limitation to their design freedom. Since architecture students learn by developing design strategies, the key for achieving successful architecture-seismic design integration is the application of a method where seismic principles are addressed as design strategies. That is, site analysis, targeted performance, and more importantly, the three-dimensional control of the building configuration by the assessment of the building stiffness distribution in each orthogonal direction.

This article describes the setting of a teaching methodology addressing effective architecture-seismic design integration at a faculty of architecture in Izmir, Turkey, wherein the students were asked to design an elementary school. Since the main objective is to achieve even and regular spatial arrays of earthquake-resistant elements, the method focuses on determining the amount of stiffness in each orthogonal direction for a given configuration, in such a way that students (and architects) may modify overall dimensions of the elements during the process, to eventually produce an initial earthquake-resistant design. Hence the method addresses the assessment of the earthquake-resistant configurations not only in terms of 'correctness' (structural soundness), but in terms of its degree of feasible manipulation. This later feature is essential for architects as design freedom is often perceived in association with the possibility of modifying the project beyond the initial rules –wherever they come from. This effective seismic-architecture design integration is assessed against three objectives: (1) Awareness: The process of design embraces the logic of the earthquake-resistant principles and thus produces designs that are inherently safe, from both seismic and architectural point of views; (2) Suitability: The correctness of the projects is not only measured in terms of the adequate size of earthquake-resistant elements and/or torsional effects, i.e. by a quantitative assessment, but also in terms of its level of adequacy to specific community needs, aspirations, and even beliefs, i.e. by a qualitative assessment; (3) Identity: The promotion of local socio-cultural values by architecture that is been driven by seismic design principles, and thus, not only meets the performance targets determined by a specific location but promotes identity with the community wherein the building takes place. The resulting school designs suggest that, within an integrated process of seismic-architectural design, students' seismic awareness is increased; effective earthquake-resistant building design can be developed from the early stages of the architectural design process; and, in the better cases, seismic design becomes the design driver for the entire process of producing a work of architecture.

Keywords: seismic design; school; architecture; teaching methods; earthquake architecture; post-disaster

1. Introduction

1.1 The relevance of earthquake-resistant design of schools

After the residential buildings, schools are the most common building types in any society. As building, a school poses specific problems for both architects and structural engineers. From an architectural point of view, school buildings should react to the new teaching-learning approaches by proposing contemporary arrangement of spaces, and simultaneously considering the new priorities given by handicap accessibility, safety, social, and cultural environments [1]. From a structural engineering perspective, it has been widely recognized the paramount importance of the adequate seismic design of schools as they house the most vulnerable part of any society, the children, and because the school spaces and facilities are often used as post-disaster management centers, playing a fundamental role in the distribution of aid and the necessary re-organization that takes place after an earthquake strikes. Nevertheless, the seismic performance of buildings is not an exclusive responsibility of the engineer. Architectural decisions –taken in the early stages of the project- will later determine, to a large extent, the structural behaviour of a building. Architects, therefore, must be aware of the implications that their initial design decisions have in the overall seismic response of a building. Examples of the lack of such awareness -unfortunately very often associated with negligent engineering, poor quality construction, and unsupervised building practices- can be found all over the seismic-prone countries, dramatically put in evidence after earthquakes of moderate or large intensity strike. For instance, the Great *Wenchuan* Earthquake, occurred on May 12, 2008, in China, and caused more than 40 school buildings collapse, resulting in a death toll of 14,000 students and teachers [2]. After learning the lessons from these disasters, the relevance of earthquake-resistant design of schools has become a priority for societies and thus, several initiatives to promote seismic safety of schools have been developed (see for example [3]).

1.2 The importance of introducing seismic principles in teaching architecture

Although, from an engineering point of view, architectural considerations play a fundamental role in the seismic performance of buildings, within the context of teaching architectural design, the importance of an early introduction of structural concepts and principles comes from a different perspective: the assumption that linking structural matters –seen as source of technical-based knowledge, to specific (architectural) design methods may increase the aesthetic values of the outcomes within a given design agenda. Hence the question is not why but how? In the traditional model of architectural design process, seismic design - in the eyes of architects- seems to be a consistent set of rules that constrains and limits their design freedom. Due to its inherent complexity, earthquake-resistant requirements are only considered at the latest stages of the design, resulting in a confrontation with the already defined architecture rather than adding value to its design. There exists, however, an increasing interest to eliminate such confrontation by introducing the seismic requirements not at the end but during the process of design [4-7]. This interest has been materialized by several initiatives inside the faculties of architecture, such as post-graduate or later education of architects on principles of seismic design; introduction of seismic design-related courses during architects' formation; and, introduction of seismic design principles in earlier stages of the design process of architecture (mainly inside the studios). All these initiatives address the importance of introducing seismic principles in teaching architecture, while emphasizing the earlier, the better.

1.3 The achievement of an effective architecture-seismic design integration in teaching practice

Nevertheless, an early introduction of seismic principles in the process of architectural design does not guarantee by itself the achievement of a successful integration. Many problems arise during the setting of any design methodology involving the incorporation of technical-based knowledge because of the conflicting objectives between structural and architectural design, and the lack of students' background in mechanics and other sources of technical knowledge. This approach proposes an integrated process of seismic-architectural design wherein the requirements derived from the need of achieving an earthquake- resistant building are introduced in the early stage of the process. Since architecture students learn by developing design strategies, the key to achieve successfully architecture-seismic design integration is the application of a method where seismic principles are addressed as design strategies: namely, site analysis, targeted performance, and most important, the three-dimensional control of the building configuration by the assessment of the building stiffness distribution in each orthogonal direction. This article describes the achievement of effective architecture-seismic design integration in an architectural studio focused on the design of school buildings.

2. Guidelines for effective integration between architectural and seismic design

2.1 Background

The 'studio' is the place where students of architecture learn to design. An integrated process of design cannot be achieved outside this framework. Studios are conducted by teams of instructors, usually with heterogeneous level of experience and fields of expertise. Their roles are to diversify the perspectives of the students. Such a group dynamic is based on a discussion forum that promotes strategies for design, so that the studio frequently runs through an initial construction of ideas, the discussion of proper strategies of design, and finally, the design of a project itself. The development of strategies is thus the key to introduce seismic design principles within the studio for two main reasons. First, because a seismic-based design strategy is easier to apply by the students in their designs than a set of rules, and secondly, because the study of seismic-based design strategies demands modest technical knowledge and thus can be afforded in the scarce available time students have within an always overloaded curriculum.

A studio that explores the possibilities of effective integration of earthquake-resistant principles and architectural design should focus on the design of an architectural project targeting a minimum of basic objectives, such as:

1. Respects the location in a specific site; integrating the building in the urban grid and, ideally, contributing to the setting of adequate evacuation routes and emergency management plans at urban levels.
2. Achieves a clear consistency between architectural concept and the logic of the earthquake-resistant configuration; the degree of consistency is an indicator of the building's design suitability for earthquake-prone areas. Ideally, this consistency allows students to deliver a specific design related to the site and thus promotes identity as architectural feature of seismic designed buildings;
3. Houses a double-function program that includes the elaboration of the emergency-state layout of the building as both structural engineering and architecture design problem. Ideally, the physical expression of this consideration of such a double-function emphasizes cultural and social aspects –reinforcing architectural identity [8]- and expresses a contemporaneous image of the building.

In order to meet these objectives, the setting of a design methodology is required. Its steps are organized by going from out-to-inside the building: context of the building - building function - function of the structure - structural detailing. Nonetheless, due to the fact that the conceptualization of the architectural spaces and, perhaps, the searching for an overall image, is strongly linked to the feasibility and suitability of certain spatial arrangements for achieving successful seismic configurations, the stage where the structural layout embraces the guidelines of a particular design idea will be specifically reviewed in the following sections.

2.2 Structural Layout and Earthquake-resistant Configuration

Once the need of a specific type of space is identified, both in terms of use and contextual relationships, the spatial elements that give the project physical form are required. Here is where most researchers suggest and promote the introduction of seismic principles as design guidelines. These design rules drive the building's configuration towards an adequate distribution of strength and stiffness, while simultaneously avoiding setbacks and other irregularities that have been proved dangerous. Since both successful seismic engineering and the structural mistakes in the past have been extensively documented, I do not refer here to the recommendations given by many guidelines, handbooks and codes for seismic design. Good examples of guidelines for architectural design of seismic-resistant structures can be found in [4,9]. Nevertheless, the fact that such guidelines are widely available does not imply that they are widely applied. In order to constitute an adequate set of earthquake-resistant elements, used by the architect as design elements, simple forms must be promoted by the selection of shear walls, rigid diaphragms, frames and braces featured as planes and linear elements. The simplicity exhibited by such elements will echo in the overall form of the project, promoting in turn simple forms that fit better the suggestions of symmetry, continuity, and regularity given by the principles of seismic design of buildings. In Section 3 of this article, a method to achieve such regularity of configurations is explained.

3. Simplified stiffness-based method for exploring spatial configuration in the design of earthquake-resistant school buildings

Since the objective is to achieve even and regular spatial arrays of earthquake-resistant elements, the method focuses on determining the amount of stiffness in each orthogonal direction for a given configuration. Students and architects can modify overall dimensions of the elements during the process to eventually produce an initial earthquake-resistant design. Hence the method addresses the assessment of the earthquake-resistant configurations not only in terms of 'correctness' (or being structurally sound), but in terms of its degree of feasible manipulation. This later feature is essential for architects as design freedom is often perceived in association with the possibility of modifying the project beyond the initial rules –wherever they come from. In structural terms, the design outcomes are evaluated by the degree of eccentricity they present in plan, with the clear objective to avoid designs of increasing torsional effects. Since the application of the method aims to unveil a logic structural pattern that could guide the design of a specific architectural project, only a portion of the entire project is needed as a case study. Such a portion must present features that are of interest for both architectural and structural aspects of the design. For introducing the problem, three levels of earthquakes associated with respective ground motions are defined, based on a fictional location, as follows:

Table 1: Type of earthquake and associated level of ground acceleration

Type of earthquake	g : acceleration of Gravity
Moderate	0.4g
Large	0.8g
Severe	1.2g

It is important to notice that this simplified method shows how earthquake forces determine the size of the earthquake-resistant elements, and thus, by modifying geometrical properties of both configuration and elements, initial earthquake-resistant designs can be developed. However, the method does not consider the design of ductile mechanisms and therefore structures designed by the principles described here might not safely dissipate the earthquake energy. Moreover, without ductility none of the further described configurations could safely resist any type of earthquake at all.

Finally, given the performance of school buildings during past events in the Turkish context [10], it is advisable to use walls rather than moment-resistant frames for the design of schools. Hence, for simplification, this explanation addresses the calculation of the stiffness (K) of shear walls, but the method can be extended to braced and moment frames as well.

3.1 Six steps strategy

Firstly, it is possible to determine the stiffness (K) of any ordinary structural element, in this case a shear wall, provided that its physical properties and geometry are known, as stated by:

$$K = \frac{Gbl}{kh} + \frac{3Ebl^3}{12h^3} \tag{1}$$

where E is the modulus of elasticity of the material, G is the shear modulus of elasticity, k is the shape factor (1.2 for regular rectangular shapes), and finally h, b and l are the height, thickness and length of the shear wall, respectively.

Inversely, dimensions of the wall can be determined using Eq. (1), if K is known. In order to find K, the static relationship between displacement (u), the applied force (F), and K can be used as follows:

$$F = u * K \tag{2}$$

Since the maximum displacement of a structure must be limited to avoid excessive damage and/or collapse, *u* can be set according to the regulations of a particular seismic code, usually by defining a peak story drift ratio. The peak story drift ratio for stiff systems (such as shear walls and braced frames) is 0.01 – 0.02 [or height/100 – height/200]. Consequently, using these criteria, *u* in Eq. (2) can be defined, and thus the remaining problem is finding the applied seismic force F. Using Newton's second law of motion, earthquake force is defined by the relationship between the mass of the building and the ground acceleration, as it follows:

$$F = m * a \tag{3}$$

where *a* is the peak earthquake ground acceleration and *m* is the seismic mass of the structure defined by the following relationship:

$$m = \frac{w}{g} \tag{4}$$

where *w* is the total weight of the structure and *g* is the acceleration of gravity. Since the weight can be easily calculated, the strategy for assessing the configuration consists of going backwards, throughout six steps:

Step 1: find the seismic mass of the structure *m* using Eq. (4); wherein w is the factored sum of dead and live loads of the building. The total weight is then divided by g, thus *m* is defined in kN/g.

Step 2: find the set of seismic forces F_{EQ}, by using Eq. (3) that considers the three different values of ground acceleration *a* given in Table 1, such that $F_{EQ} = m*a$, where a = 0.4g, 0.8g, and 1.2g, respectively.

Step 3: determine the maximum target displacement according to the selected seismic code to assure safety in the structural response under earthquake loading; a conservative approach limits the peak story drift ratio equal to 0.02.

Step 4: determine the required stiffness K_{req} according to Eq. (2), for each earthquake force; $K_{req-n} = F_{EQ-n}/u$ for each case, so that the required stiffness is dependent on the selected level of earthquake defined by *n = moderate, large or severe*.

Step 5: determine the necessary dimensions of the shear walls to cope with K_{req} using Eq. (1), by matching $K_{wall} = K_{req}$. In order to simplify the procedure, an iterative process of assigning values to *b* and *l* can be applied until $K_{wall} \geq K_{req}$

Step 6: determine positions of both center of mass (CoM) and center of rigidity (CoR) and check for eccentricities creating torsional effects in both directions. The aim of this final step is to promote the use of symmetrical plans, in terms of similar distribution of stiffness (Fig. 1).

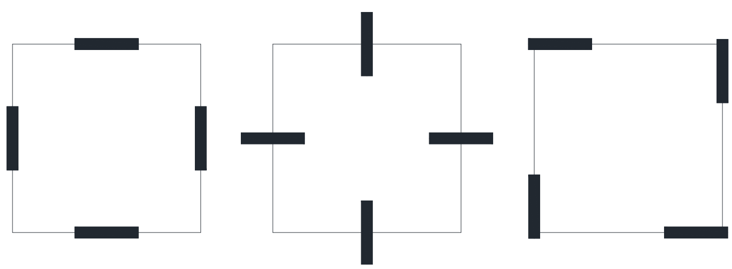

Fig. 1: schematic configurations with equal strength in each direction, but different torsional behaviour.

4. Case study and design examples

The integrated architecture-seismic design method proposed here is assessed by the setting of a case study developed at the 3rd year Architectural Studio, Faculty of Architecture, Yaşar University, in Izmir, Turkey. The studio run with the assistance and guidance of a team of five instructors (including a structural engineer). Students only possess basic knowledge on statics and building systems, so that the required theoretical background, with strong emphasis in physical principles and strategies for seismic design, is resolved by running a technical course in parallel to the studio.

The specific case study is the design of an elementary school to be located in the zone of *Kadifekale* in Izmir. The project, developed during eight weeks, consisted of the re-design of the *Inkilap* Secondary School main building and the addition of new spaces to the existing facilities: 550m^2 approx., containing twelve classrooms and administrative facilities. New functions, such as dining hall/cafeteria and sport hall, with a capacity of 650 students, were also included in the design. The design of the elementary school was undertaken by teams composed of three students. Teamwork allows the setting of the necessary discussions prior to the decision-making process, and also it makes feasible the accomplishment of the school design within the given tight timeframe.

The general objective of the application of integrated seismic-architecture design strategies in faculties of architecture placed on seismic-prone countries, such as Turkey, is twofold: reinforcing the link between the values of local identity and architectural seismic expressions, and also, raising awareness among architects about the negative consequences that a negligent design might bring under the occurrence of earthquakes.

The method can be assessed by the achievement of three objectives: two basic and one enhanced objective. Basic (1 and 2) and enhanced (3) objectives are described as it follows:

(1) Awareness: The process of design embraces the logic of the earthquake-resistant principles and thus produces designs that are inherently safe, from both seismic and architectural point of views.
(2) Suitability: The correctness of the projects is not only measured in terms of the adequate size of earthquake-resistant elements and/or torsional effects, i.e. by a quantitative assessment, but also in terms of its level of adequacy to specific community needs, aspirations, and even beliefs, i.e. by a qualitative assessment.
(3) Identity: The promotion of local socio-cultural values by architecture that has been driven by seismic design principles, and thus, not only meets the performance targets determined by a specific location but promotes identity with the community wherein the building takes place. This is the origin of the earthquake architecture.

Design examples addressing these objectives are described in the following sections, with the purpose of validating the application of the stiffness-based method in the process of designing the school buildings.

4.1 Design example 1 – Awareness

Raising the students' awareness of the seismic performance implications of their designs is the primary objective of the method. In the design example depicted in Fig. 2, the 3-story initial configuration of the school building was constituted of regular floor plans. The structure was a mixed system of shear walls and moment frames, and the non-load bearing walls were brick masonry and glass. Due to the functional layout, all the shear walls were initially concentrated in one corner of the building, along the service areas – a mistake unfortunately repeated very often in low-rise buildings all over Turkey. Nevertheless, after the assessment of the stiffness in each orthogonal direction, the student realized that '*the center of mass (CoM) and center of resistance (CoR) does not collide [are not coincident]. That's why there is torsion*'. Moreover, the solution is proposed by applying the same mechanism that causes the torsional effect: '*…structural system is unbalance[d] because there is no response with a shear wall in the left down [hand] corner. So to avoid torsion, balancing shear walls should be placed*'. In fact, the addition of an extra shear wall in the Axis-2, as depicted in Fig. 3, not only solves the torsional problem but also improves the functional layout of the school building. Therefore, the basic level of expected learning outcomes, after the application of the stiffness-based method, is achieved by the students' awareness of the seismic behaviour of their own proposed building configurations.

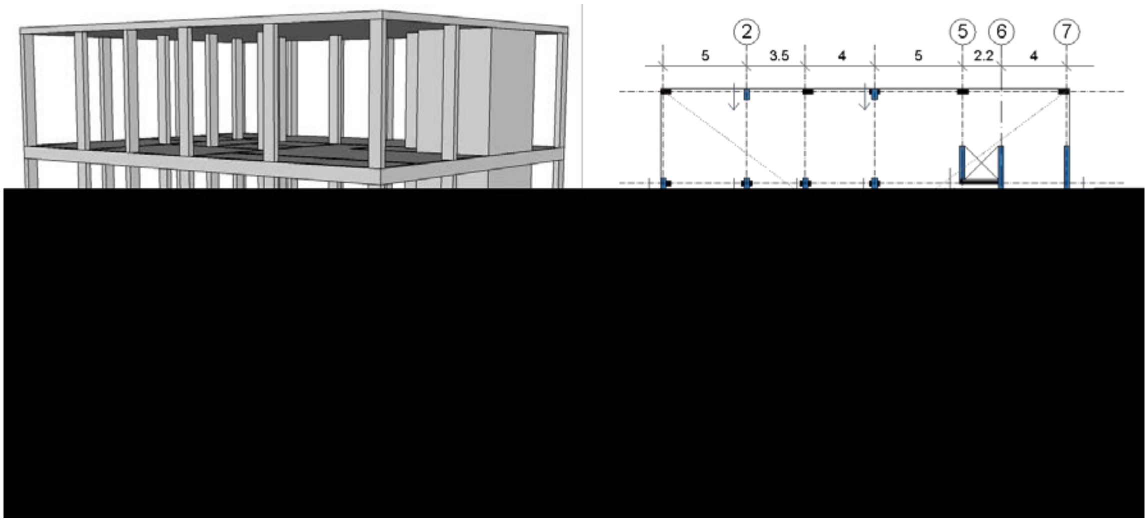

Fig. 2: Asymmetrical initial building configuration and determination of CoM-CoR raising awareness of the torsional problem in the Y-axis (Study developed by *Eda Gürağaç*)

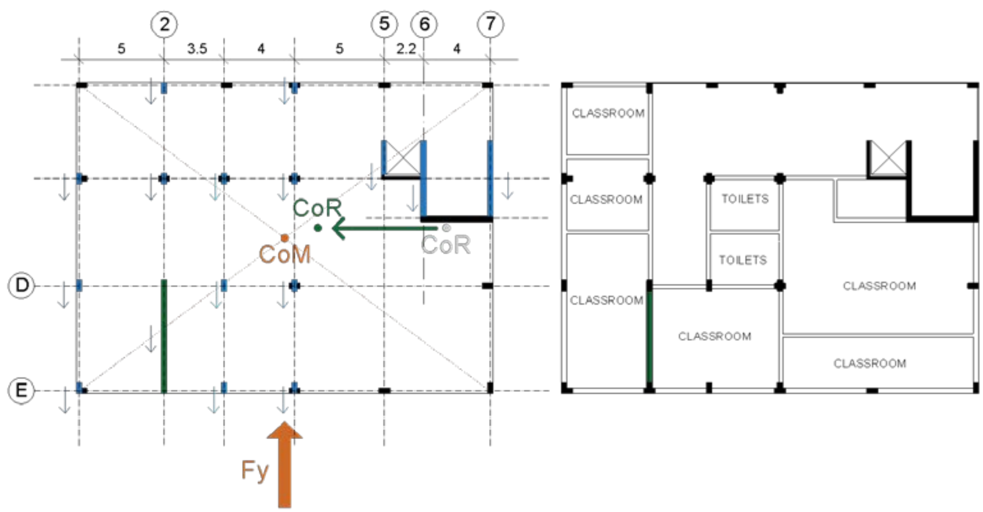

Fig. 3: The proposed solution simultaneously satisfying seismic-resistant and architectural demands (Study developed by *Eda Gürağaç*)

4.2 Design example 2 - Suitability

A second aim of the method is to make students aware that the solution proposed for the portion of the building selected for analysis, can be extended not only to the design of the entire building structure, by applying the same logic behind the structural configuration, but also to those specific requirements defined by the uniqueness of the users. In the design example depicted in Fig. 4, the school building is proposed for the use of primary and secondary students. As it can be also used as emergency shelter; the orientation of the new building responds to the idea of creating a volumetric continuity between new and existing buildings. Thus, after the assessment of the stiffness given by the structural system in the yellow area of the first floor plan (Fig. 4), the overall configuration of the project was re-arranged. First, according to seismic design principles: lateral force-resistant systems were placed preferably at building's perimeter, symmetrical layouts were organized in separated volumes, seismic joints were used, etc. and secondly, to architectural design ideas: the relationship open-closed transition areas, the provision of courtyard and foyer areas, the aimed unity and integration between the new and the existing building. The projects, therefore, are not only assessed in quantitative terms (mainly by adequate non-torsional effects), but in qualitative ones by addressing a degree of adequacy to specific community needs.

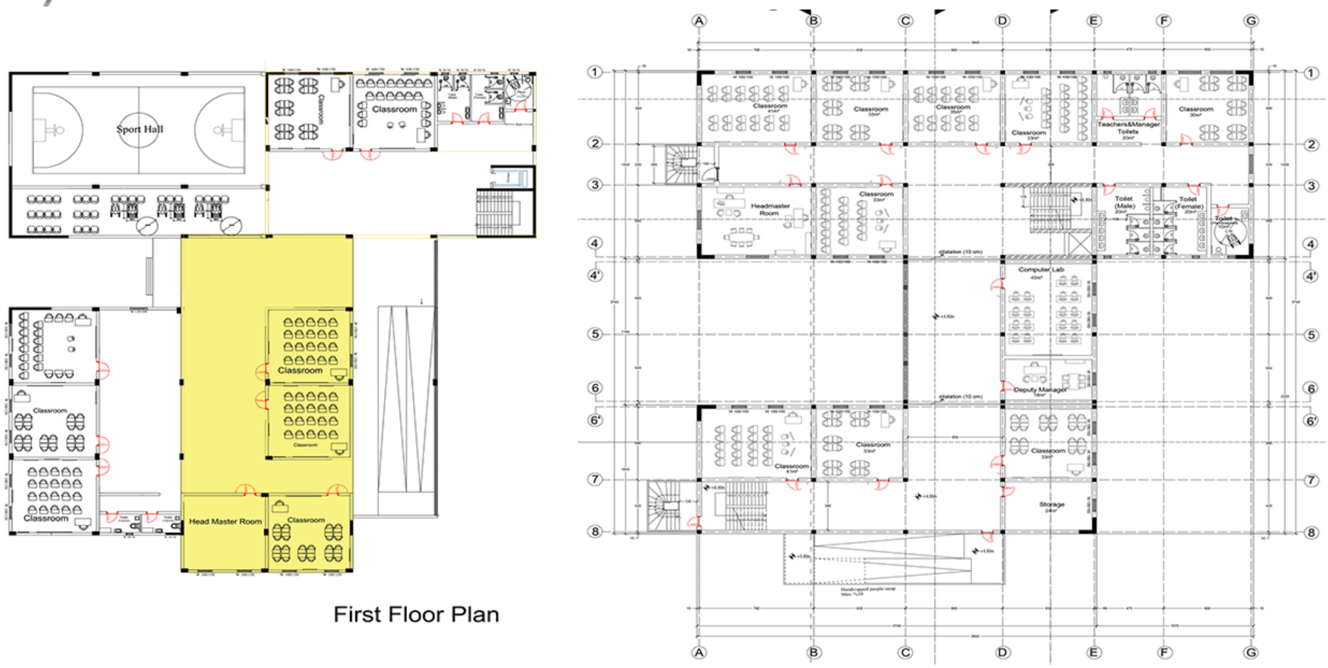

Fig. 4: The first floor school building program distribution before (left) and after (right) the application of the method (Project proposal elaborated by *Burhan Özcan*, *Dorukhan Aslan*, and *Veli Can Osanmaz*)

4.3 Design example 3 - Identity

The enhanced objective of the method addresses the introduction of seismic principles as a subject of architectural design. The consequences of the stiffness assessment may become a source of inspiration for the design of a particular architecture, validating its aesthetic achievements by reinforcing the link with the community that uses the school building. In the last design example, the formal configuration of the project was set by the strong desire of the '*preserving the characteristics of the environment*', and aiming for '*irregular patterns*' as they were associated with *Kadifekale*'s language (Fig. 5). The stiffness-based method was applied here with a twofold agenda. It forced the definition of a suitable structural system, shear walls, and assessed the sizes of their elements. Consequently, the addition of shear walls to avoid torsional effects (Fig. 6) was done by considering the precepts given by the architectural design idea. Finally, the use of a random pattern of shear walls, perfectly balanced to avoid torsion, drove the design towards its final state (Fig. 7), not only reinforcing the architectural concept, but also promoting local socio-cultural values. Identity, as an enhanced objective, involves the achievement of an architecture driven by seismic design principles, and thus, promotes identity with the community who uses the building.

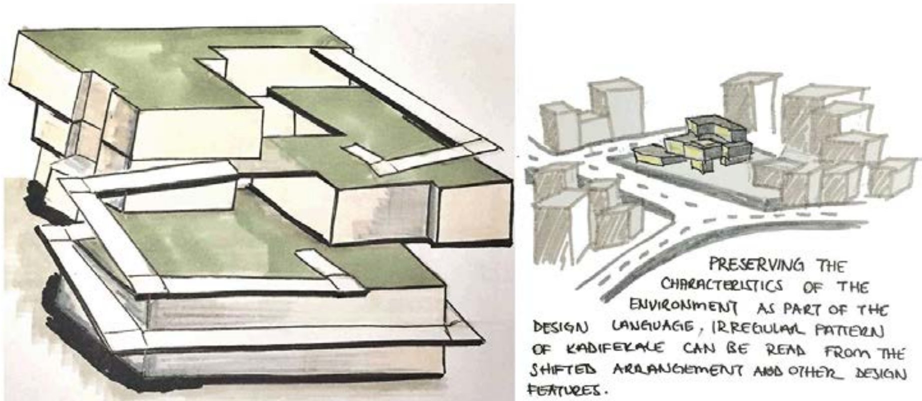

Fig. 5: Initial 'mass-based' idea for the project's design and statements on the project form-finding demands (Project elaborated by Feyza Temelli, Gizem Aykut, and Nur Yemişçi)

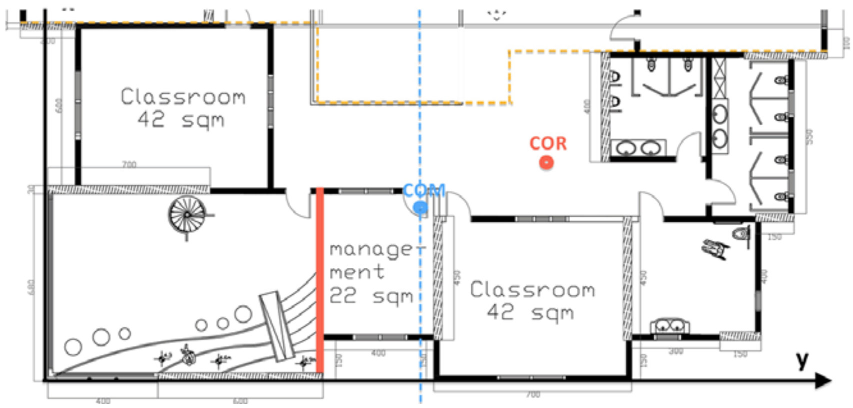

Fig. 6: Assessment of stiffness in X-axis and addition of a shear wall for avoiding torsional effects (Study developed by Nur Yemişçi)

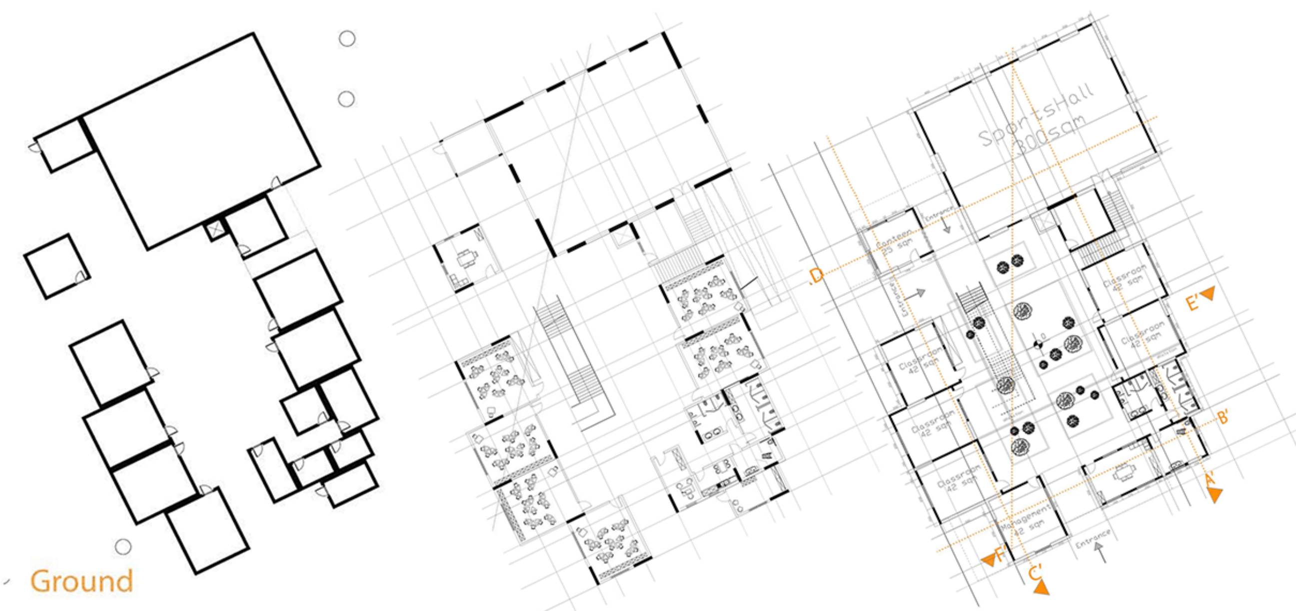

Fig. 7: Evolution of the design – from a random pattern of boxes to an architecture defined by shear walls (Project elaborated by Feyza Temelli, Gizem Aykut, and Nur Yemişçi)

5. Conclusions and final remarks

While in practice engineers focus on how to improve the seismic performance of the puzzle-like design given by the architects, in teaching practice, architects can be taught on how to introduce seismic requirements at the very moment when deciding about the configuration of a building. A method for integrating architectural-seismic design during the formation of architects has been presented for bridging this gap. The method proposed here has been initially tested by its application in an architectural studio, addressing the design of a school. Additionally, it requires the assistance of parallel courses, previous knowledge, team-based work (discussion, ideally involving engineers), and an interdisciplinary team of instructors. The selected architectural project has to meet basic objectives: respecting the urban position and location in the specific site; showing consistency between architectural concept and the logic of the earthquake-resistant design; considering the importance of the building (as double-function program).

The general objective of the application of integrated seismic-architecture design strategies in faculties of architecture in seismic-prone countries, such as Turkey, reinforces the link between the values of local identity and architectural seismic expression, and also, raises awareness among the architects about the negative consequences that a negligent design might convey under the occurrence of earthquakes, such as economic losses, extended reparation processes and worst, loss of human beings.

The effective seismic-architecture design integration has been assessed by the achievement of three specific objectives: **awareness**, by which the students design architecture that embraces the logic of the earthquake-resistant principles; **suitability**, by which the project is measured both in terms of structural correctness and local adequacy; and, **identity**, by which an architecture driven by seismic design principles promotes identity within its community.

Finally, besides the fact that more teaching experience using this method is needed in order to effectively assesses its validity, future research can be promoted in terms of the application of energy-dissipation devices or base-isolation systems in the design of buildings as an integrated process of architectural-engineering design.

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