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Research Paper

Influence of initial spatial layout on seismic behavior of masonry buildings with curved roof systems

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Abstract

Early design decisions made on building configuration and spatial design affect seismic behavior of buildings. Therefore introducing design guidelines and empirical methods implemented to assess seismic behavior of buildings have been proposed as an appropriate approach. Such concept helps architects to take into the consideration that how their preliminary design decisions influence downstream structural results. In previous efforts guidelines for seismic assessment of irregular buildings configuration and also torsional effect of interior walls-layout have been introduced. While seismic effects of the adjacency in spatial units and associated structural systems are almost ignored. This paper tries to show how spatial layout and specifically adjacency of spatial units affect the seismic behavior of a building when (1) the roofing systems are non-uniform and (2) specific spatial units correspond to the specific types of roofs with specific seismic behavior. The paper focuses on masonry buildings with curved roofing systems. To develop guidelines and empirical methods, we selected conventional masonry residential buildings implemented in central arid and semi-arid zones of Iran, traditionally, as case study. Two approaches have been proposed in the form of seismic guidelines and empirical methods. First, a method is introduced to show how adjacency of spatial units and associated vaults with different seismic vulnerability can affect the vulnerability of whole structure according to the effect of "successive damage". An empirical method is also proposed to estimate the value and shape of distribution of lateral forces on load-bearing walls transferred by adjacent curved roofs, since lateral forces increase seismic vulnerability of load-bearing walls.

Keywords: *Seismic behavior of adjacency, Empirical seismic assessment, Masonry domes, Masonry vaults.*

1. INTRODUCTION

1.1. Hints on conical dome's history and structure

Use of masonry vaults and domes supported by masonry load bearing walls have been the dominant traditional construction method in the residential buildings of arid and semi-arid zones of Iran. These local masonry curved roofing systems have been densely jointed together as a cluster of structural units including one or number of houses.

Therefore in the seismic assessment of these structures, it is important not to evaluate them as a single structure. However in almost all seismic assessment guidelines and instructions provided about effects of early architectural design on seismic behavior of buildings the adjacency effect for multi-roofing systems have not been considered yet [1-4].

As it will be described later in detail, in multi roofing structural systems such as masonry buildings with curved roofs, each room has its own roofing type. Type of each room depends on the dimension, geometry and function of that room. In another word the arrangement of different types of curved roofs correspond directly to the floor plan layout as the arrangement of spatial units. This means that while floor plan shapes always have had the great influences on seismic behavior of all buildings, in the so-called traditional buildings such influences become more highlighted due to the highly integration and interaction of spatial and structural layout.

Adjacency in different types of roofs is important because:

- Firstly, non-uniform roofing systems result in non-uniform structural behavior in different parts of a single building. For example in masonry buildings with curved roofs, while the proper seismic performance of some, has been reported several times during previous earthquakes, the evidences of disastrous destructions

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caused by other roofing types have also been quite clear in the existing damage reports. Adjacency of weak and resistant roof structures in these residential buildings indicates that these habitats do not have uniform overall seismic performance. The paper will discuss later that in these cases the seismic resistance of each unit becomes mostly as same as the weakest unit [5].

- Furthermore, the adjacency of curved roofs mostly affects the value and distribution shape of lateral reactions on the supporting load bearing walls. Such lateral forces can amplify the horizontal loads of earthquake and accelerate the collapse mechanism of arches. Knowing the value of lateral loads on each load bearing wall and the distribution shape of lateral loads along a wall help to estimate the seismic behavior of walls bearing the load of adjacent curved roofs. As much as this value tends to be zero and the distribution shape tends to be uniform along a wall, such type of adjacency will be more favorable.

This paper is developed in three sectors trying to propose guidelines and empirical methods to evaluate seismic behavior of these masonry buildings. Section 2 introduces the previous studies which provided guidelines, instructions or empirical methods about architectural design effects on the seismic behavior of structures. Section 3 describes the association of spatial units and their architectural features with their related structural roofing systems and their seismic behavior. In this section a method is proposed to estimate how adjacency of various types of roofs can affect the seismic vulnerability of a specific type of curved masonry roof according to the "successive damage" effect. Section 4 finally introduces a geometric empirical method to assess lateral forces on each load bearing wall giving early spatial layout floor plan.

2. RELATED WORKS

The influence of a floor plan shape and its spatial arrangement on the seismic response of buildings has been studied so far mostly according to the following issues

- The effect of overall configuration of buildings on the overall irregularities of seismic behavior of buildings.
- The effect of Interior rooms layout on torsional behavior of buildings against lateral forces
- The effect of Interior layout of rooms in different floors on the rigidity of different floors which results in weak or soft stories in buildings.
- The effect of location, geometry and size of horizontal openings on torsional behavior of buildings against lateral forces
- The effect of location, geometry and size of vertical openings on the rigidity of different floors which results in weak or soft stories in buildings.

2.1. Seismic effects of overall floor plan configuration

The overall floor plan configuration has been introduced as one of the critical early architectural decisions which affect the seismic behavior of buildings. Structural codes have been studied and proposed guidelines about the overall floor plan configuration [1, 3, 6-9] to obtain the proper seismic behavior. Any kind of irregularities in the shape of plan can cause the harmful seismic effects. The most common seismic effects of irregularities have been introduced as: (1) Stress concentrations on corners due to the separated and diverse movements of different parts of buildings [6] (such as different types of deflection or vertical and horizontal coupling shears [7]) and (2) Torsional effects.

Arnold classified all varieties of overall plan configuration irregularities in 5 groups of (a) torsional irregularities with stiff diaphragm, (b) large projections and reentrant corners such as T, L, U, Y, cruciform shaped plan and any other complex floor plan shapes, (c) diaphragm discontinuity, (d) out-of-plane offset, (e) non-parallel system [7] and (f) variant geometry of floor plan in different stories which can indirectly cause the irregularities in the whole mass of buildings mostly in multi-massed buildings [6].

Almost all building codes implement geometric constraints as guidelines to avoid irregularities in the overall building configurations. For masonry systems, such overall configurations are limited to a set of constraints collected according to the building codes for masonry structures, such as:

1. The ratio of longer to shorter edges of boundary templates shall be equal to or less than 4 [3].
2. The longer edge of boundary template shall be equal or less than 40 m.
3. The ratio of the largest edge among all edges of projections which are parallel to the edge of the main boundary in each direction should be less than 0.2 [1].
4. The ratio of projections area to the total floor area shall be less than 15% [3].
5. When a projection intersects one of the sides of main boundary, the parallel edge of projection shall be equal to or longer than other edge of that projection [1], etc.

2.2. Influence of spatial layout on seismic design

The seismic effect of Interior Floor plan layout is another issue which has been taken into the consideration in previous researches. In these researches spatial layout presents the arrangement of structural components such as walls and columns. Irregular distribution of walls and columns mostly in one floor directly causes seismic torsion. Such torsion is caused due to the existence of distance between the centers of mass and rigidity [6, 7]. Such torsional effect also may be caused by irregular distribution of components with different weights [6]. Providing empirical methods to calculate the distance between the center of mass and the center of rigidity has been proposed in number of researches such as [9-11].

In some previous studies about masonry buildings, a set geometric limitations and constraints has been assigned subjected to the size, shape and location of walls and their openings horizontally and vertically. In masonry seismic codes such as [1] these limitations have been provided by introducing restrictions on the sizes, dimensions and ratios of width, height and thickness of walls. Similarly Nateghi [12] regulated geometric guidelines to assign upper bounds on the maximum distances between structural vertical components due to the structural capacities of walls such as out-of-plane bending capacity [12]. These upper bounds reduce the out-of-plane and in-plane failure of walls or any other failure modes to the minimum.

Irregularity in the horizontally distribution of walls on different floor-plans in multi-story buildings can also causes an interruption in continuous vertical resistance of a building and therefore causes soft stories. To avoid such an inappropriate seismic effect, some empirical methods and guidelines limit the rigidity differences between all floors and mostly between two adjacent stories. For example the ratio of rigidity between two adjacent floors should be less than 0.8 [1].

Beside all these considerations, adjacency of architectural units and their associated structural systems can affect the seismic behavior of a building as it will be discussed in this paper for the first time. In following sections, our new approach present how spatial layout can affect the seismic behavior of masonry buildings with curved roofs. In section 3 the relationship between spatial units and their associated roofing systems and their seismic behaviors will be discussed. In this section we propose an approximated method to estimate how the seismic vulnerability of adjacent roofs can affect the seismic behavior of a specific curved masonry roof.

In section 4 an empirical method has been proposed to control adjacency effect on the distribution shape of lateral loads on load bearing walls. Although openings can significantly change the seismic response of the roofing systems, this paper just focuses on load bearing walls, leaving this issue for further researches. Since the seismic influences of overall configuration, torsional effects due to the components distribution, and out-of-plane and in-plane failures of walls have been studied widely in previous researches, they are not taken into the account in this essay. It will be clear that to have a more reliable seismic assessment at early stages of architectural design, guidelines and empirical methods which are proposed by this paper should be considered alongside other guidelines and empirical methods which have been provided in the other issues described above.

3. ESTIMATION OF STRUCTURAL UNITS SEISMIC VULNERABILITY

This section introduces a procedural method to assess the seismic vulnerability of each structural unit based on its own seismic behavior and also the seismic impact of its adjacent units. It is assumed that inputs are provided at the preliminary stages of spatial design.

3.1. Seismic vulnerability of masonry vaults

To determine the precise seismic responses of all kind of vaults and domes, knowing their overall three - dimensional configuration is necessary. However as this paper tries to focus on the floor plan influences on the seismic performance of buildings, the evaluation are based on the floor plan shape and spatial arrangements capabilities.

Vaults and domes implemented in construction of the traditional residential buildings in central arid parts of Iran are categorized in four basic types. Each of them has been used for special types of spatial units. These vaults and corresponding spatial units are classified as follows:

1. **Barrel vaults-** which are implemented to cover roofs of corridors when only two longitudinal sides of spatial units are occupied by load bearing walls
2. **One way '*Helali Poush*' vaults-** which are applied to cover roofs of *Ivans* (porches); this type is a combination of half of a barrel vault with dome shaped (pavilion vault shaped) ends. The brick courses are leaning toward the domed shaped end (Fig 1-a) [13]. This type is implemented when three sides of spatial units are surrounded by the load bearing walls.
3. **Two way '*Helali Poush*' vaults-** which are used to cover roofs of rooms with rectangular floor plan shape. This type of vault is a combination of two one-way '*Helali Poush*' vaults [13]. Two dome shaped (pavilion vault shaped) ends show this type of vault can be assumed as a pavilion vault which slightly has been stretched (Fig 1-b). This type is applied when all four sides of spatial units are surrounded by load bearing walls.
4. **Double curved pavilion vaults-** which are implemented to cover roofs of rooms with square floor plan shapes when all four sides of spatial units are surrounded by load bearing walls [13] (Fig 1-c).
5. **(Semi-spherical) dome roofs** for spaces with hexagonal or octagonal floor plans such as 'Hashti's [13].
6. According to the damage reports of past earthquakes occurred in arid and semi-arid areas of Iran, estimating the performance of masonry curved roofs in residential buildings would be possible. This research has tried to evaluate the seismic performance of all introduced five types of roofs by use of these reports. We ranked them by applying 6 scores. The seismic vulnerability increases by increasing the value of scores. In these reports, generally curved roofs are divided into two main types of vaults and domes. In almost all these reports vaults have referred to the barrel vaults or partial barrel roofs and dome shaped roofs have referred to the dome structures and also other kinds of symmetric double curved roofs such as pavilion or cross vaults. According to these description, two roofing types of **Double curved pavilion vault** and **(Semi-spherical) dome** will be explained as "Dome shaped roof" and other three types of **Barrel vault**, **One way '*Helali poush*' vault,** and **Two way '*Helali poush*' vault** will be categorized as "Vault shaped roof".

Seismic performances of 'Dome shaped roofs': Dome shaped roofs in almost all previous earthquakes have had proper seismic responses in comparison to the cylindrical vaults and flat roofs. There are several evidences of intact fallen domes which their supporting walls collapsed during earthquakes while they remained with less damage [14, 15, 16]. Razani and Lee specifically in the report of Qir and Karzin earthquake of 10 Aprils 1972 mentioned the better seismic response of dome structures of mosques, mausoleums, and local residential buildings comparing to the flat and barrel vaults roofs. [16] Manuel Berberian after Tabas-e-Golshan earthquakes of 16 September 1978 of magnitude Ms=7.7 reported better seismic resistance of dome vaults than barrel vaults and recommended to use this roofing type in future local constructions [17]. Similar observations about intact domed structures have been reported during Bam 2003 earthquake. In other destructive Iranian earthquakes like 1962 Buyin Zahra, 1968 Dashte Bayaz, 1978 Tabas, 1981 Sirch, and 1998 Golbaf earthquakes better seismic behavior of domed roofs comparing to the vaults and flat roofs with wooden joists had been reported [18]. Maheri et al described dome roof seismic performance as follows.

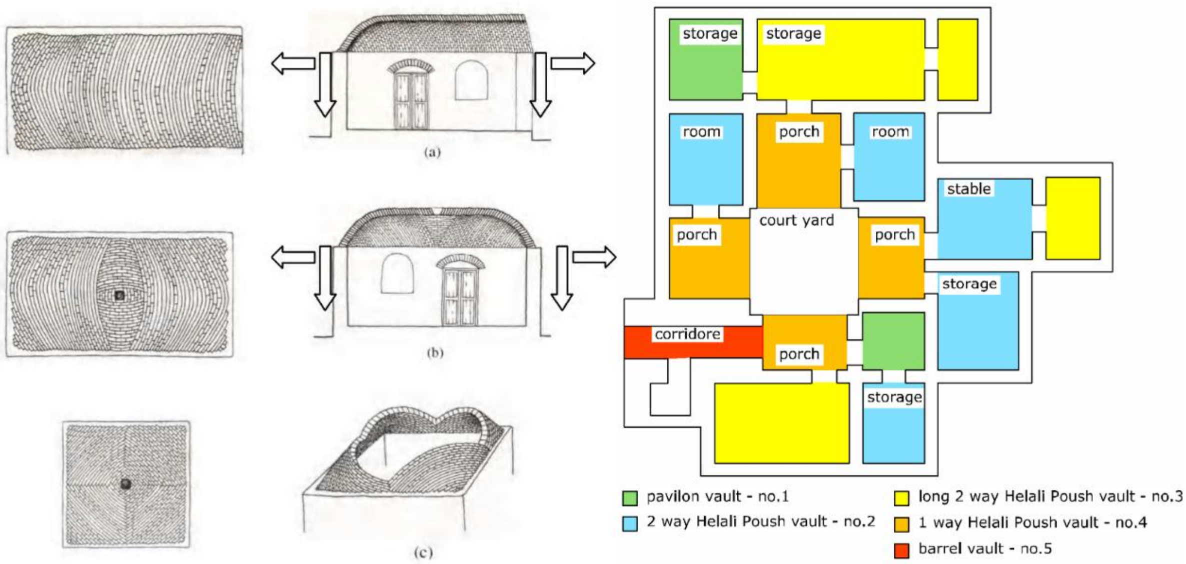


Fig. 1 left- top: a. one way helali-poush vault, b. two way helali-poush vault, c. pavilion vault, [13] right-top: an example of building plan in village of mazar- gonabad- khorasan (the initial surveyed floor plan is obtained by [19])

"The resilience of the semi-spherical domes stems from their bi-directional load-bearing capacity and support system. A dome carries its loads primarily in compression and the horizontal seismic loads do not create sufficient flexural stresses in the dome to result in a net tensile stress. As a result, the dome is required to carry the loads in compression and adobe is capable of transferring compressive stresses" [18]. In present paper, this type of curved roofing system is ranked as no.1 (Fig. 2).

Seismic performance of vault roofs: *Barrel Vaults* are much more vulnerable to the seismic loads rather than domes. Any slight movement of their supporting walls results in their cracks and collapses [14]. Usually the seismic performance of barrel vaults are even weaker than the seismic performance of flat roofs due to the generation of extra lateral thrust at their supports [18]. Razani and Lee based on the observations after earthquakes of 1962, Buyin Zahra and 1968 Dashte Bayaz believed that the seismic resistance of barrel vaults is less than domes and flat timbered roofs [15]. Their report on the seismic behavior of vault under earthquake loads during two aforementioned earthquakes describes:

"Adobe houses with cylindrical vaults did not have good seismic performances, especially when rise of arch was small. When direction of the main shock was perpendicular to generatrix of the cylindrical roofs, the vault was ruptured at its base line."[15]. In this paper this type is ranked as no.6 (Fig. 2).

Furthermore in previous seismic damage reports like Qir 1972 earthquake, there were examples of "mid-portion of cylindrical vaults with dome shaped ends" roofing types like *one way 'helali poush' vaults* which have been observed collapsed while ending dome remained undamaged. Such seismic behavior shows that porches covered by *one way 'helali poush' vaults,* have better seismic responses comparing to the spaces covered by barrel vaults. However, they still should be categorized as one of the most seismically vulnerable units in traditional habitats. In this paper, they are ranked as no.5 and no.4 when the geometry of floorplan becomes closer to the square (fig 2). Seismic behavior of *two way 'Helali Poush' vaults,* can be assumed as the combination pavilion and barrel vaults seismic behaviors. When the length of rectangular floor plan becomes longer, their performances would be more similar to the barrel vaults behavior and in this research in this case they are ranked as no. 3 (Fig. 2). In contrast whenever the length of rectangular floor plan becomes shorter, their performances are going to be more similar to the pavilion vaults behavior. In this case these vaults are ranked as no.2 in this paper (Fig. 2).

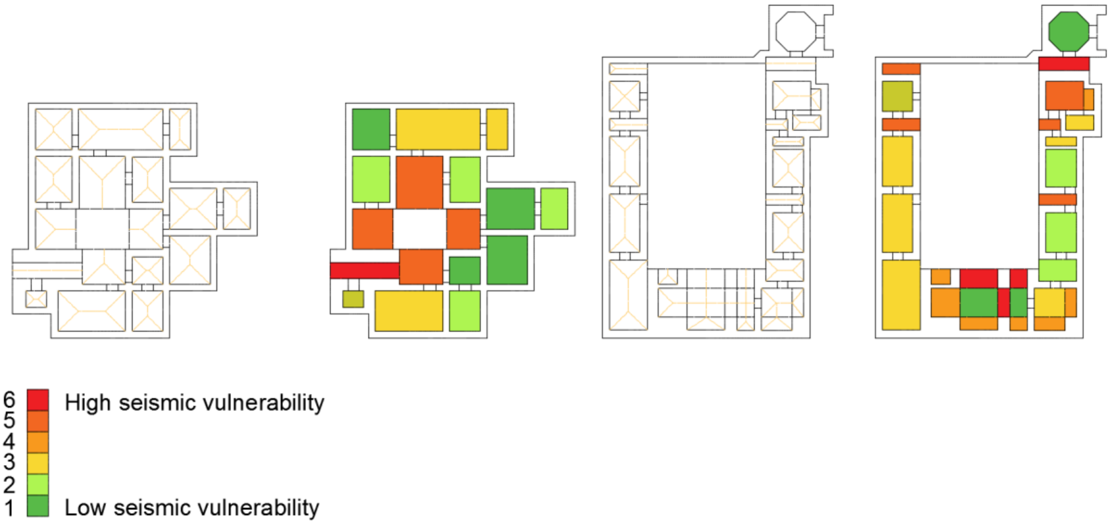


Fig. 2 Ranges of vulnerability of different roofing systems. The best seismic performance is showed by no.1 and the worst seismic performance is numbered as no. 5 (the floor plans are obtained from [19])

3.2. "Successive damage" effect on seismic vulnerability of masonry units

Adjacency of rooms with different structural roofing systems can cause "successive damage". This means if a weak unit (roofing system) is collapsed, its load bearing walls will be damaged and collapsed. These load bearing walls may be shared with other units, therefore the failure of walls can results in the collapse of an adjacent unit sequentially. While such unit might have the proper seismic performances on its own.

For example assume a corridor covered by a barrel vault is adjacent to a room covered by two-way '*helali poush*' vault. If the longitudinal wall of the room is the shared wall, by collapse of the barrel vault this wall may be damaged or collapse. After destruction of this wall, the two way '*Helali Poush*' vault loses one of its main bearing support and therefore maybe fallen thoroughly or partially. On the other hand if the shorter wall becomes the shared wall, since two main load bearing walls of two way 'Helali Poush' vault remain intact, the possibility of collapse will be decreased greatly, since three main load bearing supports still remain intact.

To estimate the seismic vulnerability of each unit which is caused by successive damage effect, this work proposes the following equation which indicates the ratio of shared to not-shared lengths of edges for a unit:

$$PV_i = \frac{\sum_{l \in L_i} l}{C_i - \sum_{l \in L_i} l} \tag{1}$$

Where

PV_i Is "probability of vulnerability due to the successive damage effect" for unit i

C_i Is the circumference of unit i

L_i Is a set of lengthes of shared edges between unit i and each of its adjacent units

Fig. 3 illustrated the probability of vulnerability for adjacent units when a l of L_i is shared between unit A and B.

If the value of PV_i is close to 1, the seismic vulnerability of unit will be high and if this value is close to 0, such vulnerability will be low. By the proper integration of assigned seismic vulnerability ranking of units from 1 to 5 and value given by the "Probability of vulnerability" equation, good estimation of seismic vulnerability of each unit can be obtained according to its own structural behavior and also successive damage effects.

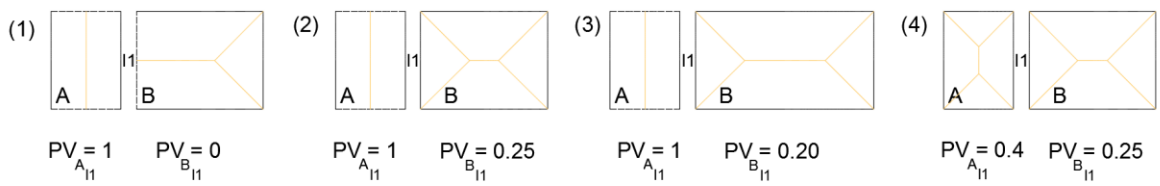


Fig. 3 Probability of vulnerability in adjacent units for $l1$ which is shared between unit A and B

4. LATERAL FORCES ON LOAD BEARING WALLS

When the gravity loads are imposed to a curved structure, lateral thrust will be generated at supports. Since both lateral thrust and seismic shocks are horizontal loads, they will amplify each other and accelerate the collapse mechanism of arches.

Therefore to reduce the seismic vulnerability of a structure, such lateral forces should be reduced as much as possible. For example, one of the specific requirements for construction of vaults and domed roofs according to the "Iranian Code of Practice for Seismic Resistant Design of buildings" is to minimize the lateral thrusts in arches [1].

In addition, the distribution of lateral forces can vary along the supporting load bearing walls. To decrease the hazardous results of seismic shocks on these walls, the distribution of lateral loads should be uniform throughout the wall, maximally since any change in the value of lateral thrust results in the change of thrust lines of the arch and its mechanism of bearing loads [20].

Therefore finding the value and geometry of distribution of lateral loads on walls will help architects to make more structurally sound decisions during preliminary spatial design. To know the exact amount of lateral thrust of a vault, it is necessary to have the through information about the configuration of that vault and location of supports [21]. Since finding out such a peculiarity is out of scope of this research we developed an empirical method to estimate the value and the geometry of lateral forces distributions. For a single unit covered by **One-way '*Helali Poush*' vault, Two-way '*Helali Poush*' vault** or **Double curved pavilion vault** such lateral forces distribution would look like as illustrated in Fig. 4.

For simple **Barrel vaults** this also would be as depicted in Fig 4.

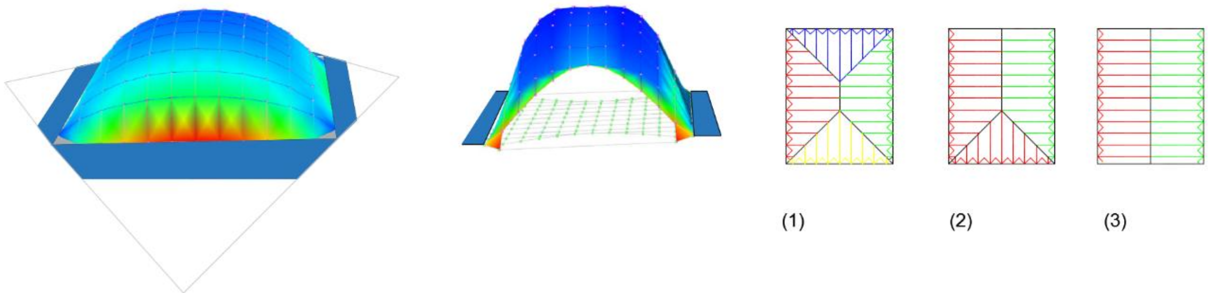


Fig. 4 simplified model of lateral force distribution on the load bearing walls for Two way 'Helali Poush' vaults and Double curved pavilion vaults (1), One way 'Helali Poush' vaults (2), Barrel vaults (3) (3d models of vaults have been obtained from [22])

In order to simplify these shapes to be implemented in our simplified model, we abstracted the value and the geometry of distribution as illustrated in Fig. 5. The resultants of lateral forces on each load bearing wall which are transferred from its adjacent vaults, will be the subtraction of geometries of distributed loads on both sides of this wall. Such subtracted shape will have various forms according to the different possibilities of adjacency between two different units with similar or different structural roofing types. Such form is an approximated shape can estimate whether the load distribution throughout the wall is ascending or descending. It also shows the relative magnitude of distributed load on different parts of a load bearing wall.

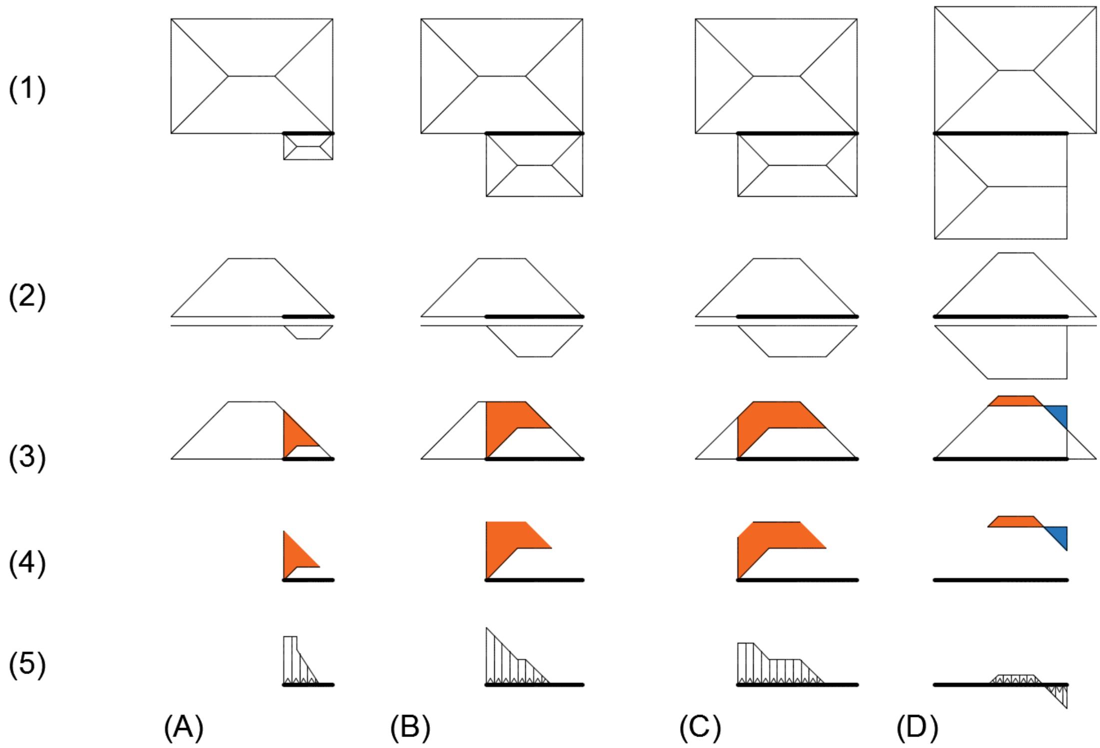


Fig. 5 The simplified model showing the resultants of lateral forces on each load bearing walls by geometrically subtraction of distributed loads on both sides of that load bearing wall

To generalize all these various shapes in a common geometric definition we proposed number of fixed geometries as templates with parametric edges. While edges by becoming zero-length can produce various shapes with different geometries based on a unique template (Fig. 7).

Our templates are generated and defined for any edge (walls) of a unit. This edge (wall) generally can include two sections. (1) a segment shared between two adjacent units and (2) a segment which are not-shared between two adjacent units. For shared section of an edge, according to the different geometry and structural types of vaults for two adjacent units, we have found out 114 different cases with different distribution shapes. To generalize all this 114 cases (Appendix A, table 1), we have developed 3 fixed templates as illustrated in Fig. 6, while the length of each segment of proposed polygon is defined according to the equations no. 2 to 17.these Lengths are calculated based on the length and width of either of adjacent slabs of a load bearing wall as known parameters.

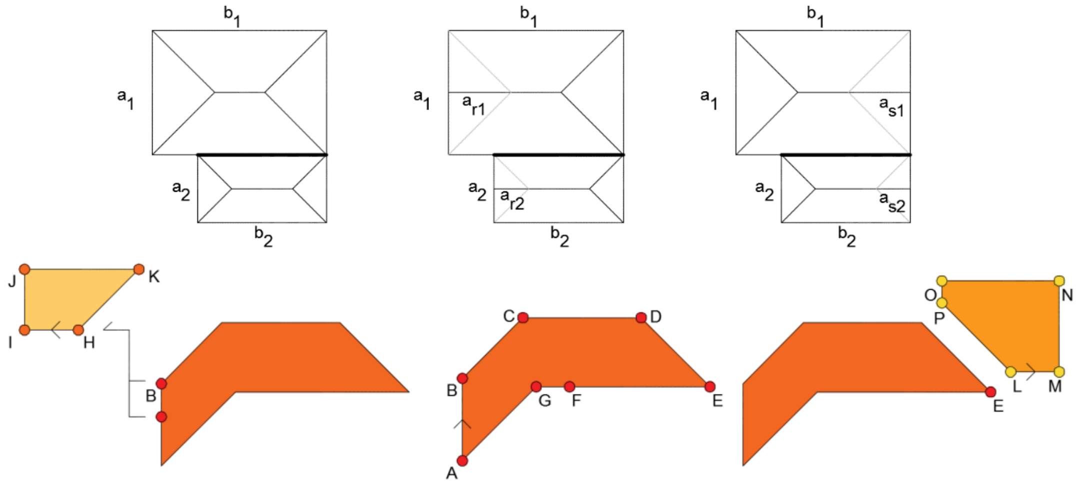


Fig. 6 Three fixed templates for the shared section of load bearing wall between 2 units to generalize all possible shapes of lateral loads distribution. The length of edges can be zero.

$$AB = \max\left[\min\left[(b_1 - b_2), \frac{a_1}{2}, b_2\right] - \frac{a_{r2}}{2}, 0\right] \tag{2}$$

$$BC = \sqrt{2}\left[\frac{a_1}{2} - \min\left[(b_1 - b_2), \frac{a_1}{2}\right]\right] \tag{3}$$

$$CD = b_1 - a_1 - \left[\max\left[\min\left[(b_1 - a_1), \left(b_1 - \frac{a_1}{2} - b_2\right)\right], 0\right]\right] \tag{4}$$

$$DE = \frac{\sqrt{2}}{2}\left(\min\left(\frac{a_1}{2}, b_2\right) - \frac{a_2}{2}\right) \tag{5}$$

$$EF = b_2 - a_2 \tag{6}$$

$$FG = \min\left[\min\left[(b_1 - b_2), \frac{a_1}{2}, b_2\right], \frac{a_{r2}}{2}\right] \tag{7}$$

$$GA = \frac{\sqrt{2}}{2} a_2 - \frac{\sqrt{2}}{2} a_{r2} \tag{8}$$

$$y_H = \min(AB, h_{GA}), \qquad x_H = x_A \tag{9}$$

$$HI = \max\left[\left(\frac{a_{r2}}{2} - \min\left[\frac{a_{r2}}{2}, (b_1 - b_2)\right]\right), 0\right] \tag{10}$$

$$IJ = \left[\frac{a_{r1}}{2} - \min\left[(b_1 - b_2), \frac{a_{r1}}{2}\right]\right] - \max\left[\left(\frac{a_{r2}}{2} - \min\left[(b_1 - b_2), \frac{a_1}{2}, b_2\right]\right), 0\right] \tag{11}$$

$$JK = \max\left[\frac{a_{r1}}{2} - \min\left[(b_1 - b_2), \frac{a_1}{2}\right), 0\right] \tag{12}$$

$$x_L = x_E, \qquad y_L = y_E \tag{13}$$

$$LM = \left|\min\left(\frac{a_{s1}}{2}, b_2\right) - \frac{a_{s2}}{2}\right| \tag{14}$$

$$MN = \frac{a_{s1}}{2} - \frac{a_{s2}}{2} \tag{15}$$

$$NO = \min\left(\frac{a_{s1}}{2}, b_2\right) \tag{16}$$

$$OP = \frac{a_{s1}}{2} - \min\left(\frac{a_{s1}}{2}, b_2\right) \tag{17}$$

For not-shared section of a wall also 14 different cases with various shapes could be found (Appendix A, table 2). We we have developed other 3 templates as illustrated in Fig. 7 which can cover all these 14 cases. Lengths of segments of polygons representing these three templates are defined according to the Fig. 8 and equations no. 18 to 30.

$$x_{A'} = x_{A}, \qquad y_{A'} = y_{A} \tag{18}$$

$$A'B' = b_1 - b_2 \tag{19}$$

$$B'C' = \sqrt{2}\min\left[(b_1 - b_2), \frac{a_1}{2}\right] \tag{20}$$

$$C'D' = \max\left[\min\left[(b_1 - b_2), \left(b_1 - \frac{a_1}{2} - b_2\right)\right], 0\right] \tag{21}$$

$$D'E' = \sqrt{2}\left(\frac{a_1}{2} - \min\left(\frac{a_1}{2}, b_2\right)\right) \tag{22}$$

$$E'A' = \min\left[(b_1 - b_2), \frac{a_1}{2}, b_2\right] \tag{23}$$

$$x_{F'} = x_{B'}, \qquad y_{F'} = y_{B'} \tag{24}$$

$$F'G' = \frac{a_{r1}}{2} \tag{25}$$

$$G'H' = \min\left[(b_1 - b_2), \frac{a_{r1}}{2}\right] \tag{26}$$

$$H'I' = JK \tag{27}$$

$$x_{J'} = x_{D'}, \qquad y_{J'} = y_{D'} \tag{28}$$

$$J'K' = \frac{a_{s1}}{2} - \min\left(\frac{a_{s1}}{2}, b_2\right) \tag{29}$$

$$K'L' = \frac{a_{s1}}{2} - \min\left(\frac{a_{s1}}{2}, b_2\right) \tag{30}$$

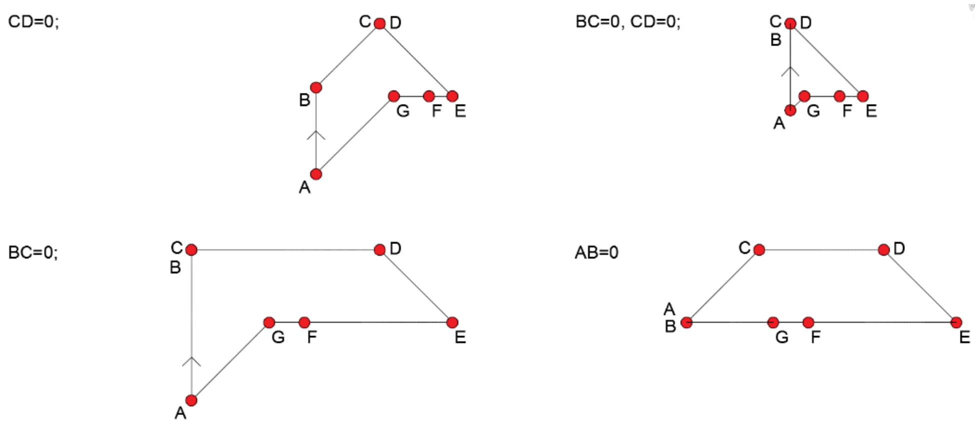


Fig. 7 One of fixed template for the shared section of load bearing wall between 2 units. Such template can be transformed to the all possible shapes of lateral loads distribution. The length of edges can be zero

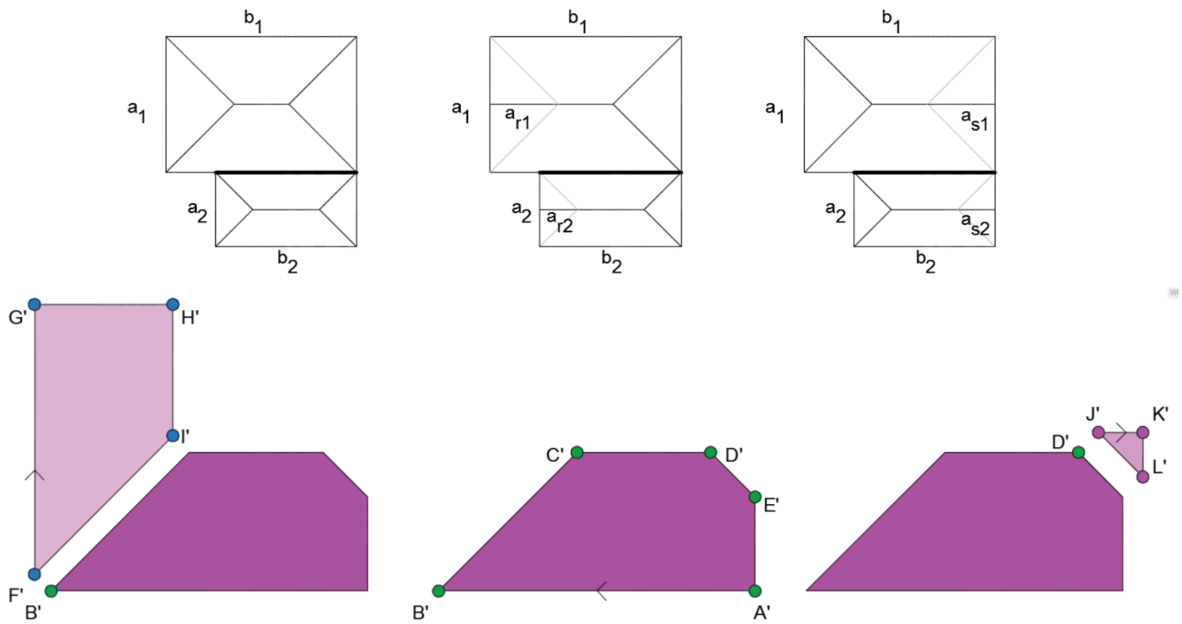


Fig. 8 Three fixed templates for the not-shared section of a load bearing walls between 2 units to generalize all possible shapes of lateral loads distribution

5. CONCLUSION

In this paper a set of empirical methods were provided to estimate the seismic behavior of masonry buildings constructed by multi-curved roofs. Introduced methods use the initial spatial layout as given inputs. The paper introduced the floor plan shape as one of the most effective factors in determining the type of roofing systems and the models of their adjacency which directly affect the seismic response of such buildings. In this paper at initial stage we tried to find a meaningful map from the different spatial units defined by their functionality and geometry to the specific types of vaults to show how the spatial program (describing spaces according to their architectural functionalities) results in specific arrangement of different types of curved roof. We tried to implement this method to evaluate the seismic response of an initial architectural layout indirectly. We proposed two approximate methods firstly to estimate the vulnerability of each structural unit based on its own structural behavior and also the seismic behavior of its adjacent units which we termed as "successive damage", and secondly to estimate the value and shape of lateral load distribution on each load bearing wall.

Such approximated methods mostly are proper at the early stages of spatial design and the structural estimation of architectural design decisions. The proposed methods should be considered alongside other issues which are out of scope of this research like torsional provisions during the interior layout design. Furthermore, in more detailed stages of architectural and structural design, such empirical methods will be insufficient. At later stages of design process the precise and accurate structural analysis to obtain more reliable seismic assessment of buildings are necessary.

APPENDIX A

Table 1. 114 cases of different shapes for subtracted distributed lateral loads on shared section of a load bearing wall

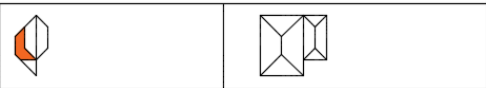
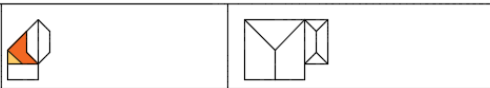
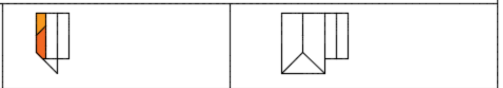
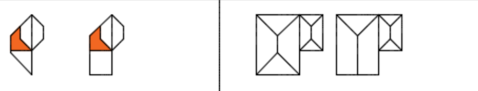
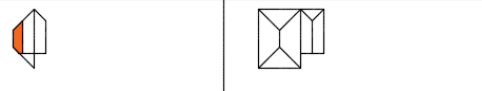
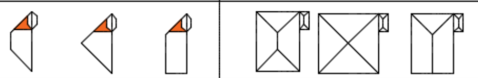
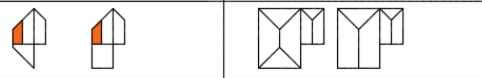
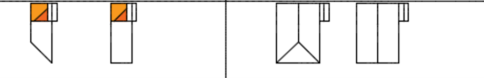
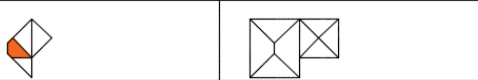
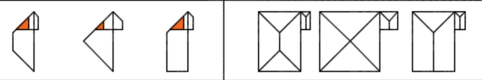
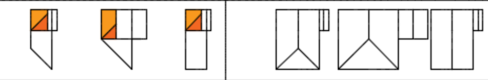
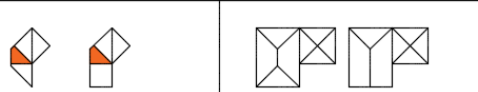
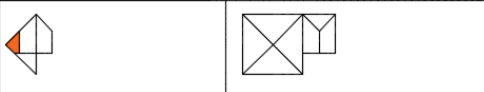
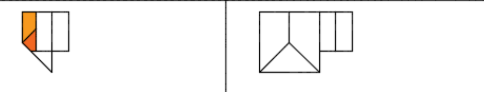
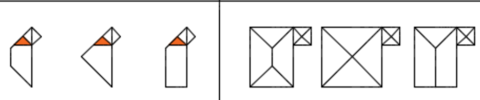
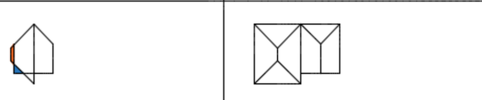
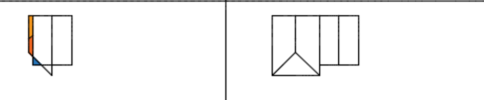
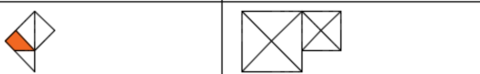
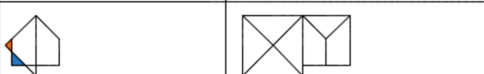
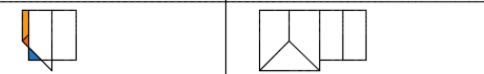
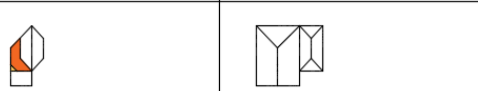
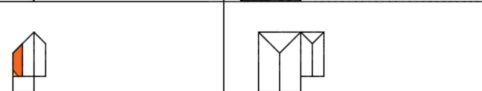
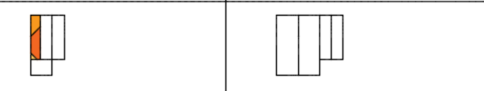
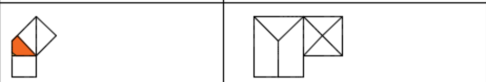
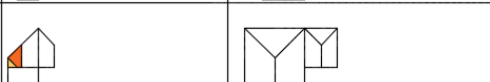
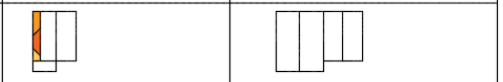
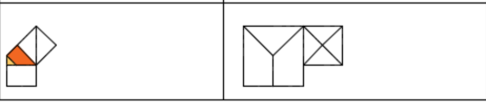
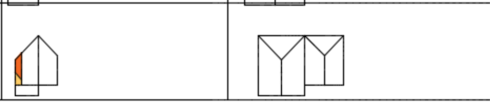
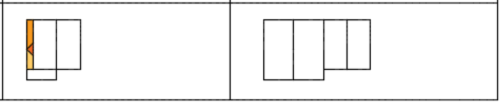
Case no.	Subtracted shape of Lateral force	Adjacency model of 2 units	Case no.	Subtracted shape of Lateral force	Adjacency model of 2 units	Case no.	Subtracted shape of Lateral force	Adjacency model of 2 units
1			11			21		
2			12			22		
3			13			23		
4			14			24		
5			15			25		
6			16			26		
7			17			27		
8			18			28		
9			19			29		
10			20			30		

Table 1. 114 cases of different shapes for subtracted distributed lateral loads on shared section of a load bearing wall

Case no.	Subtracted shape of Lateral force	Adjacency model of 2 units	Case no.	Subtracted shape of Lateral force	Adjacency model of 2 units	Case no.	Subtracted shape of Lateral force	Adjacency model of 2 units
31			41			51		
32			42			52		
33			43			53		
34			44			54		
35			45			55		
36			46			56		
37			47			57		
38			48			58		
39			49			59		
40			50			60		

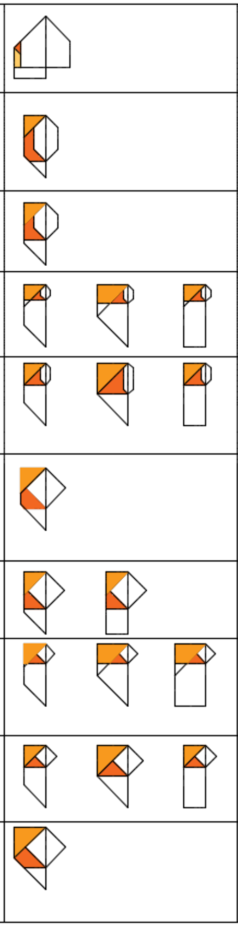
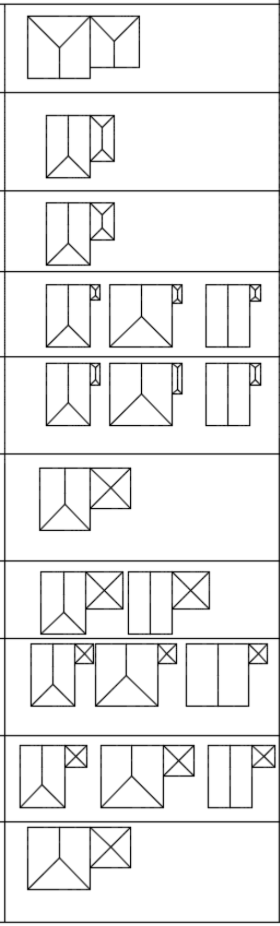
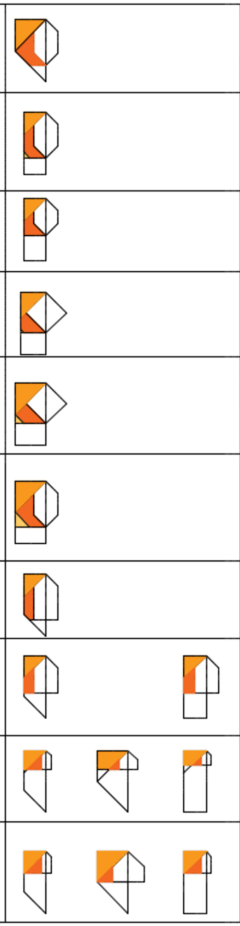
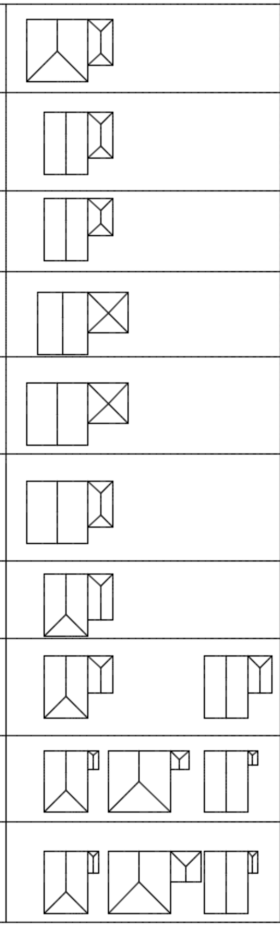
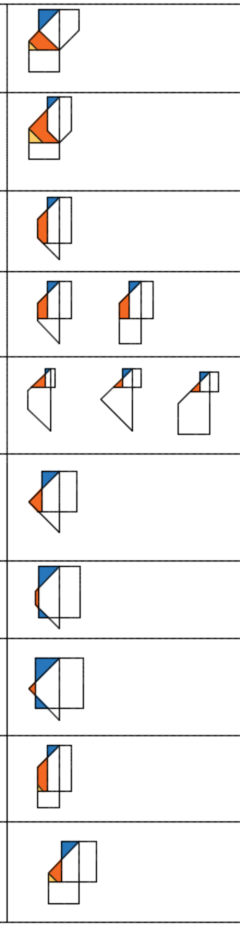
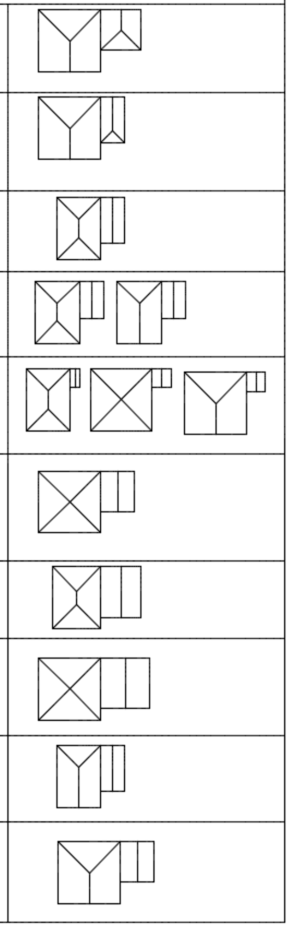







Table 1. 114 cases of different shapes for subtracted distributed lateral loads on shared section of a load bearing wall

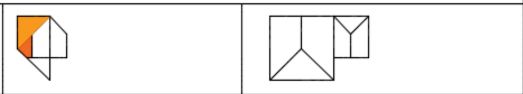
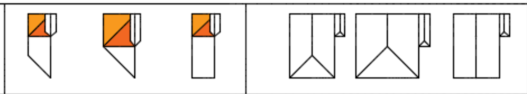
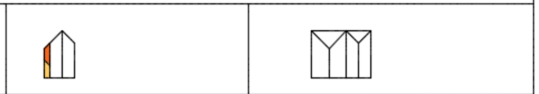
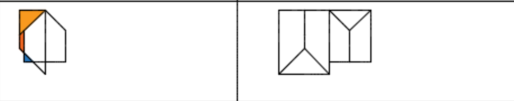
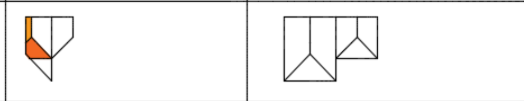
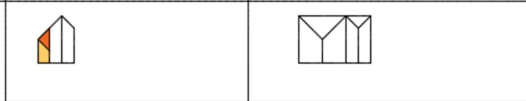
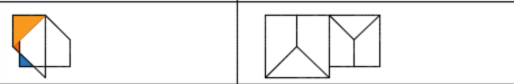
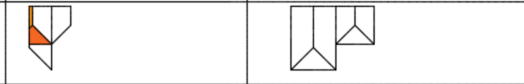
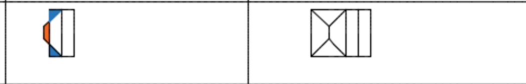
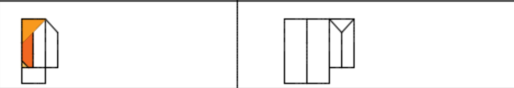
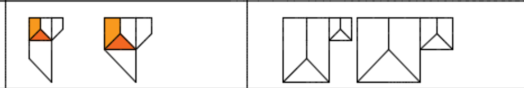
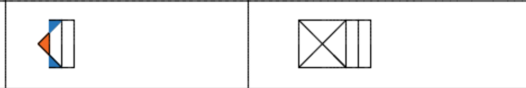
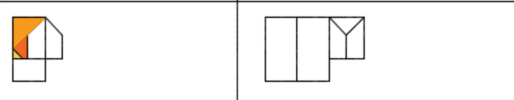
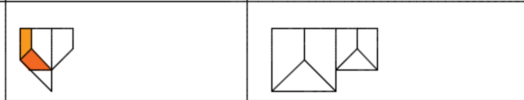
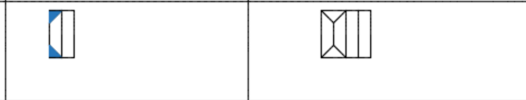
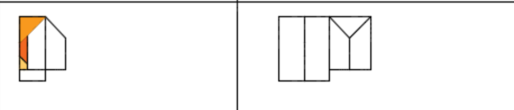
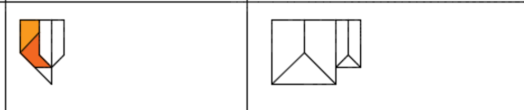
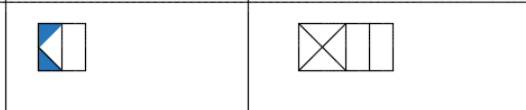
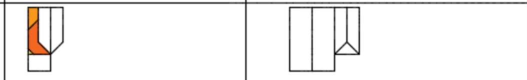
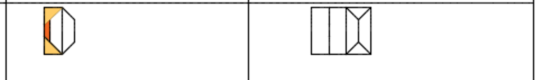
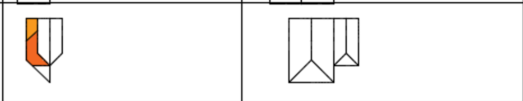
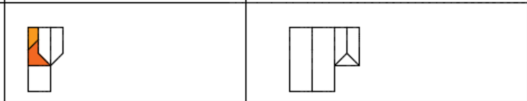
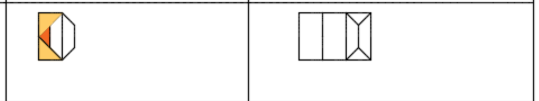
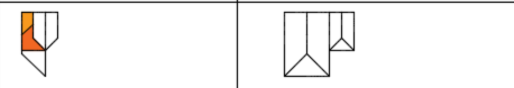
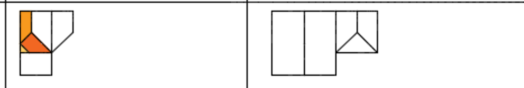
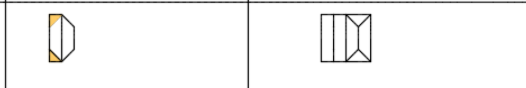
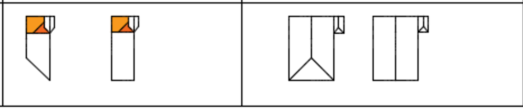
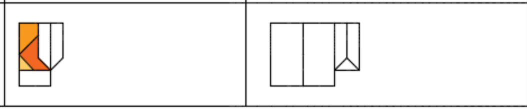
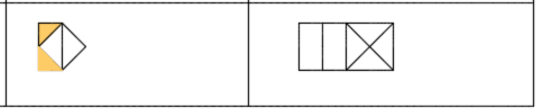
Case no.	Subtracted shape of Lateral force / Adjacency model of 2 units	Case no.	Subtracted shape of Lateral force / Adjacency model of 2 units	Case no.	Subtracted shape of Lateral force / Adjacency model of 2 units
61		71		81	
62		72		82	
63		73		83	
64		74		84	
65		75		85	
66		76		86	
67		77		87	
68		78		88	
69		79		89	
70		80		90	

Table 1. 114 cases of different shapes for subtracted distributed lateral loads on shared section of a load bearing wall

Case no.	Subtracted shape of Lateral force	Adjacency model of 2 units	Case no.	Subtracted shape of Lateral force	Adjacency model of 2 units	Case no.	Subtracted shape of Lateral force	Adjacency model of 2 units
91			99			107		
92			100			108		
93			101			109		
94			102			110		
95			103			111		
96			104			112		
97			105			113		
98			106			114		

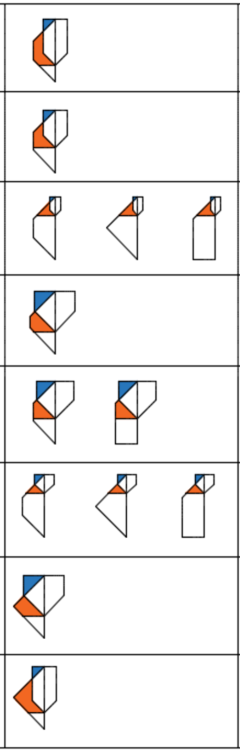
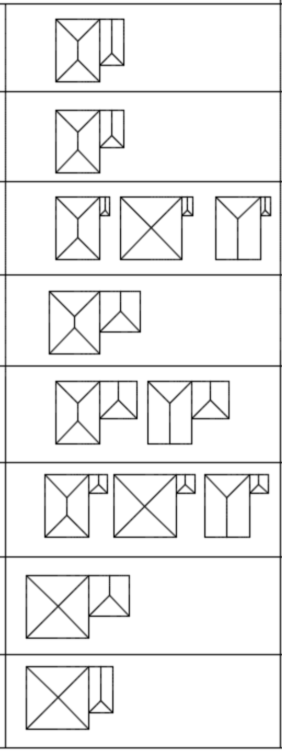
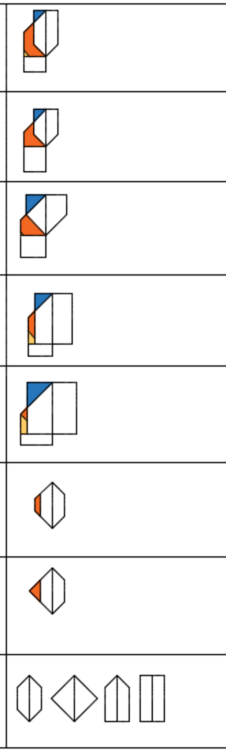
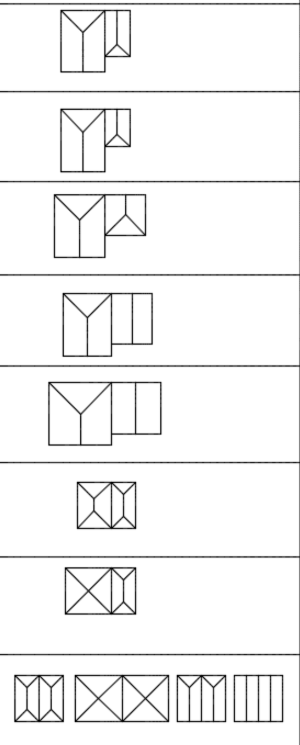
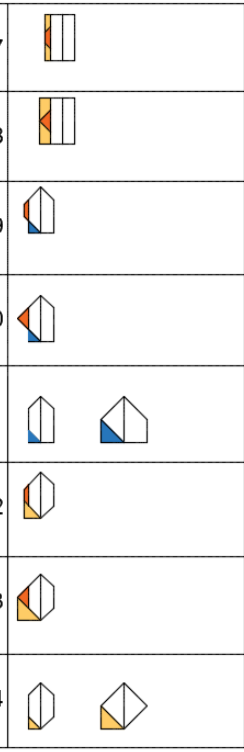
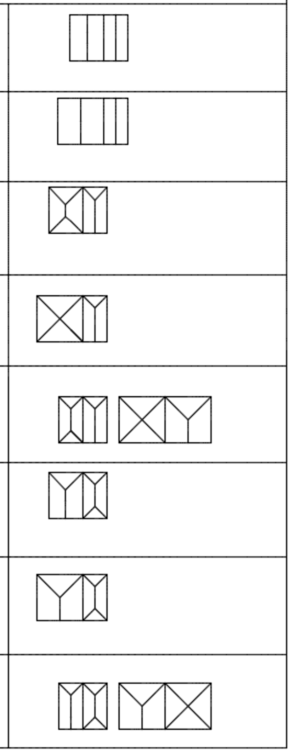







Table 2. 14 cases of different shapes for subtracted distributed lateral loads on not shared section of a load bearing wall

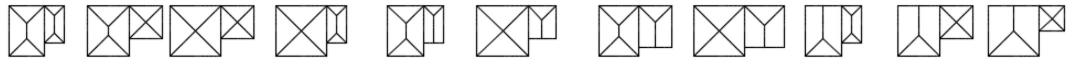
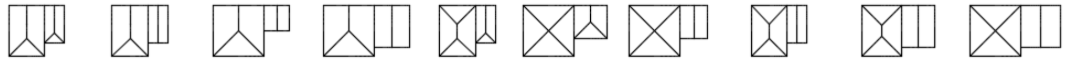
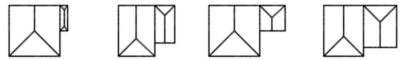
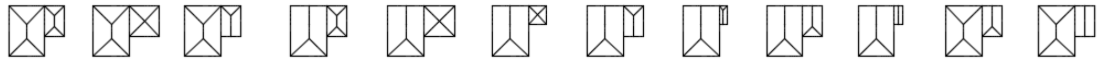
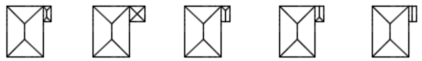
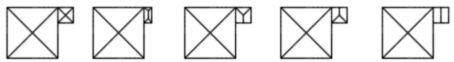
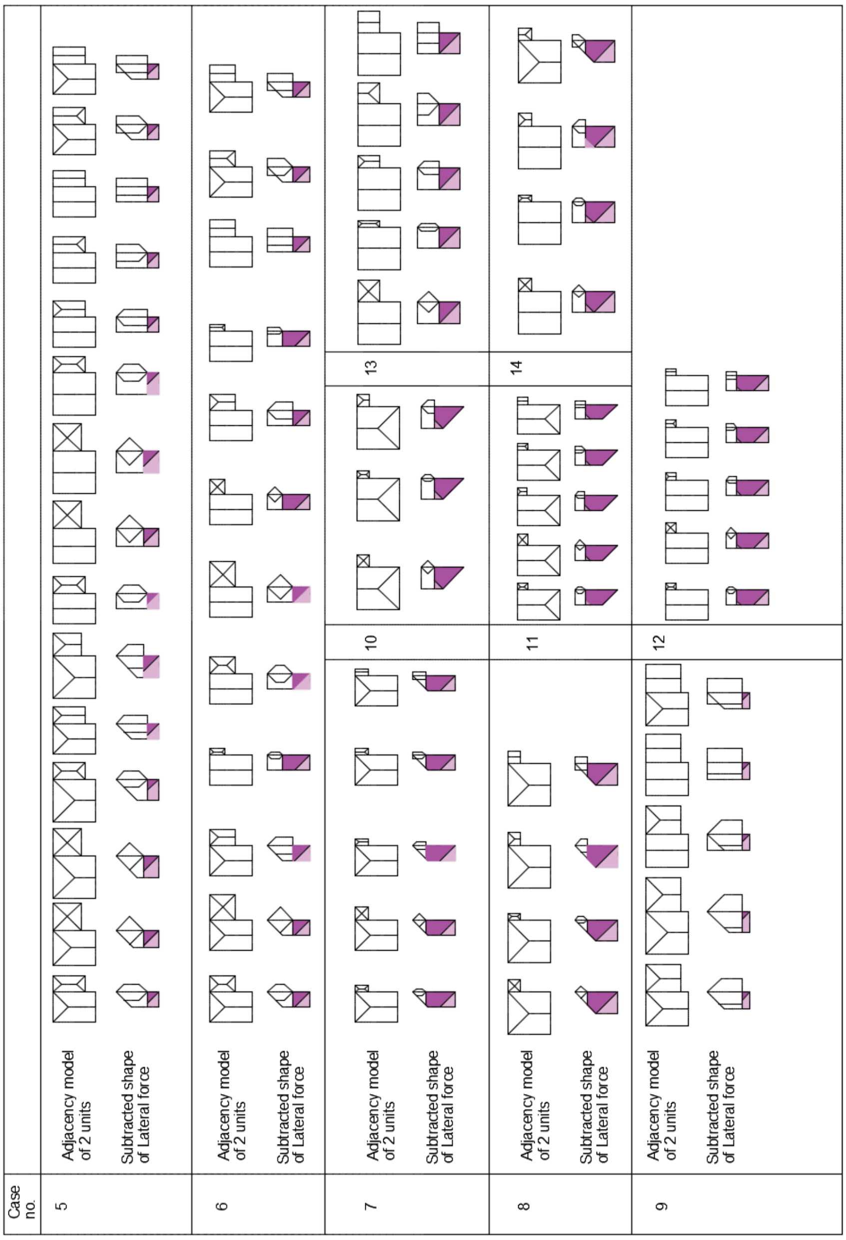
Case no.		
1	Adjacency model of 2 units	
	Subtracted shape of Lateral force	
	Adjacency model of 2 units	
	Subtracted shape of Lateral force	
	Adjacency model of 2 units	
	Subtracted shape of Lateral force	
2	Adjacency model of 2 units	
	Subtracted shape of Lateral force	
3	Adjacency model of 2 units	
	Subtracted shape of Lateral force	
4	Adjacency model of 2 units	
	Subtracted shape of Lateral force	

Table 2. 14 cases of different shapes for subtracted distributed lateral loads on not shared section of a load bearing wall



CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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