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Evaluation of seismic performance and design of AAC building systems (autoclaved aerated concrete) with different reinforcement methods

Evaluación del desempeño sísmico y diseño de sistemas de construcción de mampostería AAC (concreto aireado tratado en autoclave) con diferentes métodos de refuerzo

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ABSTRACT

Autoclaved lightweight concrete was produced for the first time in Sweden and after several decades, it has been widely used in most of the industrialized countries of the world, especially in the construction industry. Lightness, effect in reducing forces caused by earthquakes, ease of implementation, low thermal coefficient, fire resistance and sound insulation are among the undeniable advantages of this product. The use of this concrete is very effective in optimizing fuel and energy consumption, and its high compressive strength is considered an important feature, to the extent that it has been recognized as a desirable and suitable product in the construction industry. Obviously, with the growth of demand increasingly, using traditional methods and materials for housing production in Iran is not very effective. Compilation of criteria for the design and implementation of a gravity-bearing and lateral structural system made of AAC autoclaved aerated concrete products (including reinforced blocks and panels) The structure is made based on valid international regulations and considering Iran's seismic standards as follows. Roof and floor design using reinforced AAC roof panels and the combination of AAC roof blocks and regular concrete in place reinforced with steel reinforcements after examining the principles and foundations and modeling based on logical engineering principles and assumptions to compare the results and the outputs of the software have paid. Based on the available results, we can see the effect of the number of floors, plan and height of the floor on the behavior of the structure. According to the values in the table, the probability of the structure passing through the threshold of minor, moderate, and advanced damage is examined in different states. 1- The probability of passing a 1-story structure compared to a 2-story structure from the threshold of partial, moderate, and advanced damage has decreased by 59.7%, 94.5%, 99.3, and 99.8%, respectively. 2- The probability of passing a 2-story structure compared to a 3-story structure It reduces the threshold of partial, moderate, and advanced damage by 55.7%, 93.2%, 99.0%, and 99.7%, respectively.

Keywords: autoclaved lightweight concrete, compressive strength, partial damage threshold, low thermal coefficient, steel reinforcements, different reinforcement methods

RESUMEN

El hormigón ligero tratado en autoclave se produjo por primera vez en Suecia y después de varias décadas, ha sido ampliamente utilizado en la mayoría de los países industrializados del mundo, especialmente en la industria de la construcción. Ligereza, efecto en la reducción de fuerzas provocadas por terremotos, facilidad de aplicación, bajo coeficiente térmico, resistencia al fuego y aislamiento acústico son algunas de las innegables ventajas de este producto. El uso de este hormigón es muy efectivo para optimizar el consumo de combustible y energía, y su alta resistencia a la compresión se considera una característica importante, al punto que ha sido reconocido como un producto deseable y adecuado en la industria de la construcción. Obviamente, con el crecimiento de la demanda cada vez más, el uso de métodos y materiales tradicionales para la producción de viviendas en Irán no es muy efectivo. Recopilación de criterios para el diseño e implementación de un sistema estructural lateral y por gravedad hecho de productos de concreto aireado autoclavado AAC (incluidos bloques y paneles reforzados) La estructura se realiza en base a las normas internacionales vigentes y considerando los estándares sísmicos de Irán de la siguiente manera. Diseño de techos y pisos utilizando paneles de techo AAC reforzados y la combinación de bloques de techo AAC y concreto regular en el lugar reforzado con refuerzos de acero después de examinar los principios y fundamentos y el modelado basado en principios lógicos de ingeniería y suposiciones para comparar los resultados y las salidas del software haber pagado En base a los resultados disponibles, podemos ver el efecto del número de pisos, planta y altura del piso en el comportamiento de la estructura. De acuerdo con los valores de la tabla, se examina la probabilidad de que la estructura pase por el umbral de daño menor, moderado y avanzado en diferentes estados. 1- La probabilidad de pasar una estructura de 1 piso en comparación con una estructura de 2 pisos desde el umbral de daño parcial, moderado y avanzado ha disminuido en un 59,7 %, 94,5 %, 99,3 y 99,8 %, respectivamente. 2- La probabilidad de pasar una estructura de 2 pisos en comparación con una estructura de 3 pisos Reduce el umbral de daño parcial, moderado y avanzado en un 55,7 %, 93,2 %, 99,0 % y 99,7 %, respectivamente.

Palabras clave: concreto liviano tratado en autoclave, resistencia a la compresión, umbral de daño parcial, bajo coeficiente térmico, armaduras de acero, diferentes métodos de armadura

1. INTRODUCTION

Autoclaved lightweight concrete was produced for the first time in Sweden and after several decades, it has been widely used in most of the industrialized countries of the world, especially in the construction industry (Varela et al, 2004).

Being light, being effective in reducing forces caused by earthquakes, ease of implementation, low thermal coefficient, fire resistance and sound insulation are among the undeniable advantages of this product (Tomaževič and games, 2016; Bazoobandi et al. 2015; Yazdi et al. 2016). The use of this concrete is very effective in optimizing fuel and energy consumption, and its high compressive strength is considered an important feature, to the extent that it has been recognized as a desirable and suitable product in the construction industry. It is obvious that as the demand for housing production in Iran increases, using traditional methods and materials is not very effective. Considering this issue and the fact that several years have passed since the arrival of AAC lightweight concrete in Iran, unfortunately this product has not yet found its true and real position among those involving in the construction industry, especially the mass housing builders. In this article, it has been tried to introduce AAC lightweight concrete by collecting the required technical information and highlight its features and advantages. Moreover, in order to inform and to familiarize more experts and officials of the construction industry with this concrete, a comparison has been made between this product and other similar products (Penna et al, 2010; Gharib-Gorgani et al. 2017; Bina et al. 2020; Naeemi et al. 2022). The author hopes that by compiling and writing this article, he has taken a small step in the right direction of further identification of this new technology in the country (Penna et al, 2015).

First, this study deals with the position of autoclaved aerated concrete among other light construction materials, then with reviewing the production of this product in the world and evolution of technology so far, it will look at the status of this product in Iran and its production perspective in the coming years. Autoclaved aerated concrete is included in the second group (Malawoli et al, 2014; Moghadam et al. 2021; Dehghan and Yazdi, 2023). This concrete is produced in pre-fabricated form and in two types, reinforced and unreinforced. The largest share of production is allocated to non-reinforced types (about 80 %). Production in Europe along with Russia has reached 24 million cubic meters in 2011. There is no documented information about production in China. Verbal information shows a figure of about 10 million cubic meters. No reliable statistics can be found for other countries (Mohammadnejad et al, 2014; Yazdi et al. 2022). The other main producers are Japan, South Korea, America, the countries of the Middle East and Central Asia, Africa, Australia, and India. There are no accurate statistics of production. In 1992, Japan produced 2.5 million cubic meters, almost all of which was in the form of slabs and reinforced panels. Some sources have mentioned the global production demand of 100 million cubic meters in 2011 and announced an annual increase in production of 5 million cubic meters. Iran's practical production capacity in 2019 was about 500,000 cubic meters, which we will discuss in more detail. By evaluating the statistics of the production of other types of lightweight concrete, it can be concluded that, at least in terms of producing non-reinforced elements, this type of concrete currently has the first place in the world (Bastani et al, 2011). Currently, according to the development process of construction in the country and the increase in demand for construction, the use of new methods in this industry can increase the speed of construction, and also reduce waste in this field. AAC aerated concrete is one of these new methods in the construction industry of our country. Autoclaved aerated concrete (AAC) is a special type of lightweight porous concrete, which is mainly made of materials based on silica, cement, lime and aluminum powder. Today, this product is called AAC and was first developed in 1924 by a Swedish scientist. The reason for this invention was to have a material with positive properties of wood such as insulation, workability and lightness without the disadvantages of wood such as flammability and decay.

The porous structure of AAC, which is formed due to the reaction of free lime created from the combination of cement, lime and aluminum powder, has good thermal properties (thermal insulation) and also has a higher ratio of resistance to volume mass compared to other types of concrete. It has good thermal properties (thermal insulation) and also has a higher resistance against volumetric mass compared to other types of concrete. Considering that aerated concrete has light weight and suitable non-structural strength, one of its main applications can be light building blocks for the construction of separating walls (Enteziri, 2014; Yazdi et al. 2019).

The advantages of the blocks made with this concrete include fire resistance, not emitting any smoke, gases or toxic fumes when affected by fire, optimal thermal performance, not needing for separate thermal insulation, reducing sound transmission, increasing the speed of construction and reducing the consumption of materials needed for the facade as well as the mass of the building. AAC lightweight concrete and its 60-year history is a successful example of the mass construction with new materials in the United Arab Emirates, Turkey and China in the last two decades (Costa et al, 2011).

2. METHODOLOGY

Part one: Compilation of criteria for the design and implementation of a gravity-bearing and lateral structural system made of AAC autoclaved aerated concrete products (including reinforced blocks and panels) provides criteria and limitations. Moreover, the instructions for designing and implementing a structural system to bear the loads on the structure based on valid international regulations and considering the Iran's seismic standards are done as follows. Roof and floor design using AAC reinforced roof panels as well as combination of AAC roof blocks and regular concrete in place reinforced with steel reinforcements. Roof and floor design using reinforced AAC roof panels and the combination of AAC roof blocks and regular reinforced cast-in-place concrete with steel reinforcements.

Providing the necessary solutions to create coherent performance of the roof under seismic loads and proper connection of roof and roof support.

The design of the vertical bearing structure system to withstand dead and live gravity loads and the lateral bearing system to withstand lateral loading due to wind or earthquake based on the use of AAC reinforced wall panels and AAC blocks as composing elements of structural wall.

Maintaining the coherence and integrity of the building by using horizontal and vertical ties or other appropriate reinforcing and unifying elements.

Presenting the criteria and limitations related to the effective factors in the structural behavior of the building made of AAC reinforced wall panels and AAC wall blocks, including:

- Seismicity and geotechnical characteristics of the delineated area
- The height of the building and its floors
- Building plan
- Vertical cross section of the building
- Dimensions and location of openings
- Minimum wall thickness
- The minimum relative wall in each extension of the building according to the number of stories
- Horizontal and vertical ties or other suitable reinforcing elements
- Other effective factors
- Presenting detailed criteria for implementing a structural system made of AAC products

Part Two: Presenting a detailed software model for the analysis and design of a complete structural system based on AAC reinforced blocks and panels, and evaluating its structural behavior under static and dynamic loads and designing the relevant structure in this section have been done using valid structural software. A detailed software model has been prepared for analyzing and designing buildings with the mentioned structural system (by complying with the mentioned criteria and taking into account suitable architectures and different geotechnical and seismic conditions). It is essential to do this process for the required number of buildings and at least one and two stories with a structural system based on AAC blocks and AAC reinforced panels. For each of the mentioned buildings, the work steps are as follows:

- Providing appropriate and diverse construction plans (considering variables including: plan dimensions, floor height (wall height), unrestrained wall length, number of floors, relative wall size, plan order, dimensions and resistance of horizontal and vertical ties, different categories of the resistance of AAC blocks, type of roof (block beam and double-sided slab)
- Selecting reliable and appropriate software for analyzing and designing the desired structural system.
- Preparing suitable software elements for accurate modeling of the behavior of structural elements including reinforced AAC panels, AAC blocks, adhesive or consumable mortar, walls made of reinforced panels and AAC blocks, roof system, horizontal and vertical ties, other integrating reinforcing elements, foundation, etc.
- Preparing a geometric model of the structural system of the desired building in the relevant software with the presence of horizontal ties under the roof in all situations and with different methods of reinforcement (including: unreinforced and without vertical ties, unreinforced and with vertical ties, reinforced with horizontal bars and vertical ties, and reinforced with flat-truss bed-joint and vertical ties

- Conducting the necessary static and dynamic analyzes in linear and non-linear modes under combined effect of gravity and seismic loads in compliance with Iran's seismic regulations and requirements. Non-linear static analysis (pushover analysis) and nonlinear incremental dynamic analysis (IDA) are used. (The results of previous reliable research or valid regulations are used to determine the mechanical characteristics of AAC masonry blocks and walls and the results of cyclic tests and the nonlinear behavior model of AAC wall elements to perform nonlinear analysis).
- Checking the behavior and structural performance of the modeled building in the software.
- Knowing the strengths and weaknesses of the modeled buildings and using the results to clarify and correct the relevant rules and restrictions in part one.
- Presenting modeling guide, analysis and software design of the structure based on AAC autoclaved aerated concrete products for desired designs.
- Designing the structure and presenting executive plans for each of the modeled buildings.

Note: Part one and two are both correlative and will be done cyclically until the most correct and accurate results are attained.

2. RESULTS AND DISCUSSION

Modeling and designing

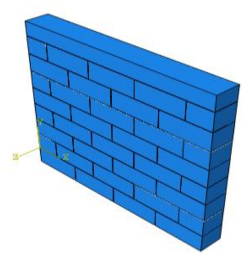


Figure 1- Drawing specifications of the wall with micro building materials considered in Abaqus software model RDB01 (3 m x 2.75 m x 0.3 m)

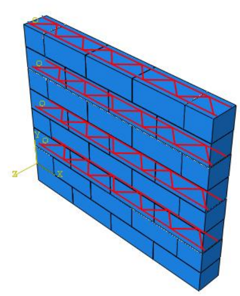


Figure 2- Drawing specifications of the wall with micro building materials considered in Abaqus software model RDB02

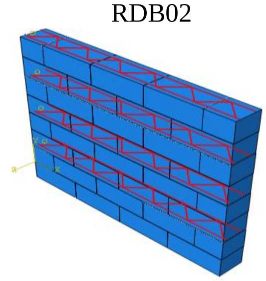
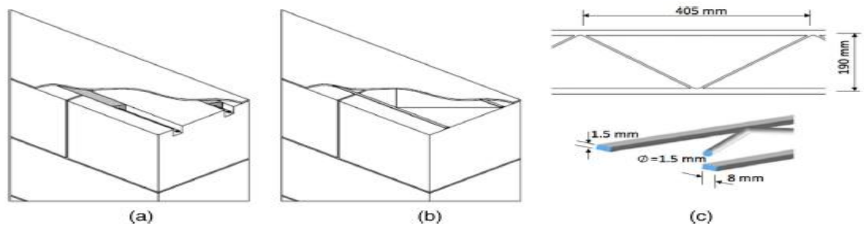


Figure 3- Drawing specifications of the wall with micro building materials considered in Abaqus software model RDB02

- Verification



- Mechanical specifications defined in Abaqus software:

	f_b [MPa]	f_m [MPa]	f_{vk0} [MPa]	f_{vm0} [MPa]	E [MPa]	G [MPa]	ρ_m [kg/m^3]	f_{yk} [MPa]	A_{gt} [%]
URM	3.48	2.33	0.17	0.25	1400	364	500	–	–
HRM	3.48	2.63	0.17	0.25	1400	448	500	600	0.75

Figure 4 - Behavioral characteristics of the block in the article (Anwari, 2019)

Cohesive behavior of joints.

Sample	Contact								
	Tangential behavior	Normal behavior	Cohesive behavior						
			Traction–separation behavior Stiffness coefficients MN/m (Kipf/in)			Damage			
						Initiation MPa (psi)			Evolution
	Friction coefficient		K_{nn}	K_{ss}	K_{tt}	Normal	Shear I	Shear II	Plastic displacement mm (in)
Ungrouted	0.78	Hard contact	8.7 (50)	8.7 (50)	(0)	12.6 (1825)	0.21 (30)	0	2.0 (0.08)
Grouted			14 (80)	14 (80)	(0)	23.7 (3434)	0.60 (85)	0	2.3 (0.09)

Figure 5. Behavioral characteristics of AAC adhesive

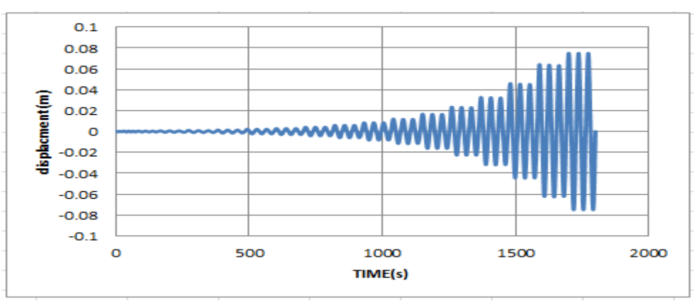


Figure 6. Loading given in the article according to Displacement-Time

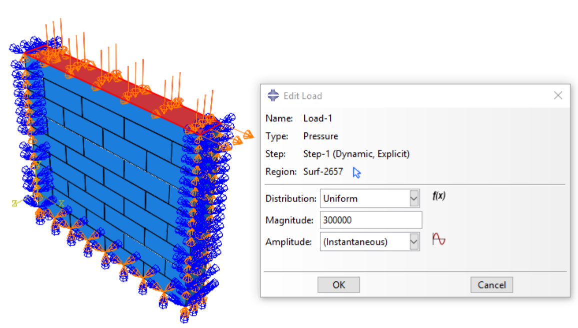


Figure 7. Defined gravity load assignment of 300KN to RDB01 model

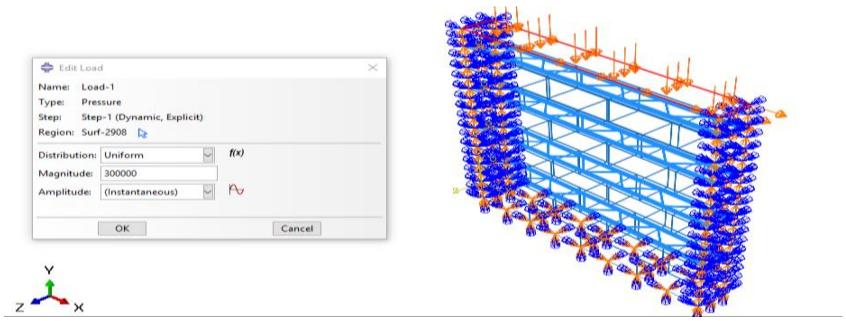


Figure 8. Defined gravity load assignment of 450KN to RDB03 model

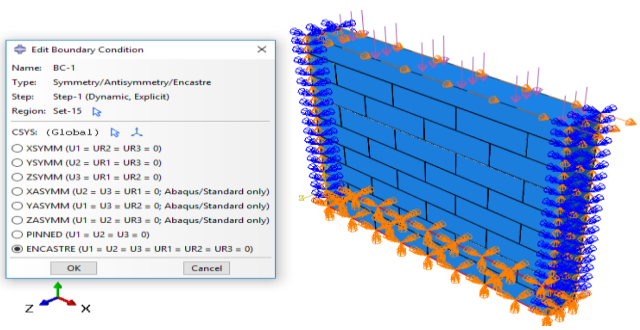


Figure 9. Holding the wall support in all directions (Encastre)

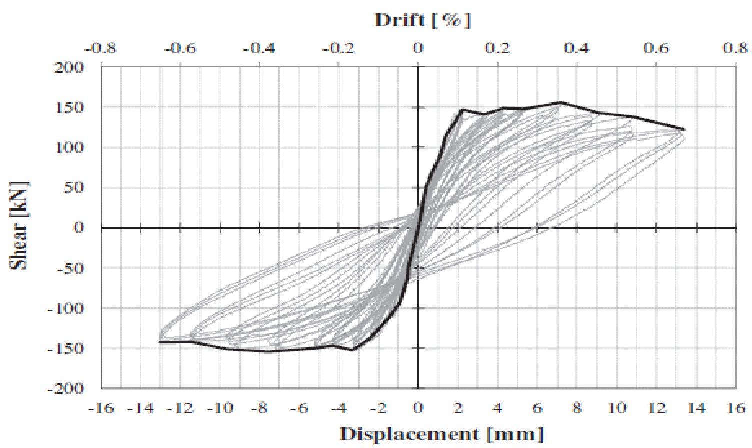


Figure 10. Output of RDBO1 model in the article

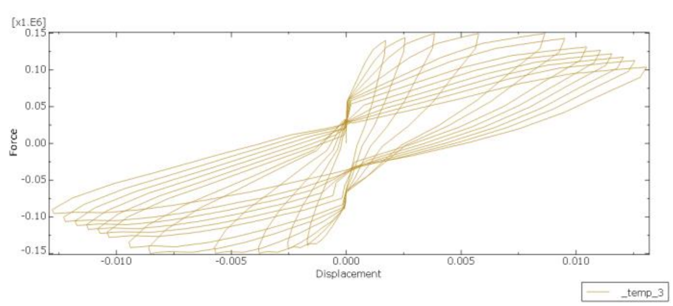


Figure 11. Output of RDBO1 model in Abaqus software

Table 1. Comparing the wall capacity (force-displacement) diagram in the article and the software. The percentage value of the difference is 5%

Displacement	Article model (m)	Abacus model (m)	The amount of difference between the article and Abaqus model (m)	Difference percentage of article model and numerical model
Maximum	0.074	0.078	0.004	5%

- The results of finite element model analysis

- The results of a 1-story structure with a regular plan and a short floor height

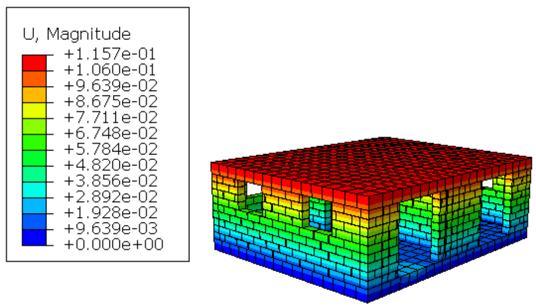


Figure 12. Color contour of the location change created in a 1-story structure model with a regular plan and a short floor height in Abaqus software.

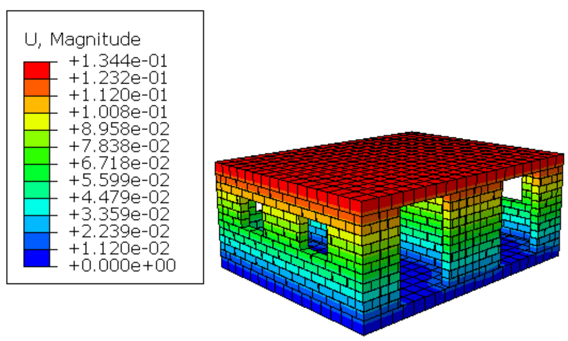


Figure 13. The color contour of the location change created in the 1-story structure model with a regular plan and average floor height in Abaqus software

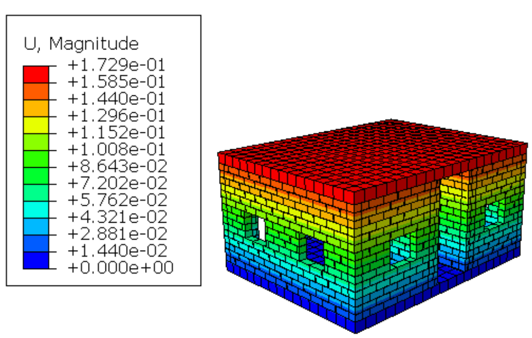


Figure 14. The color contour of the location change created in the model of a 1-story structure with a regular plan and high floor height in Abaqus software

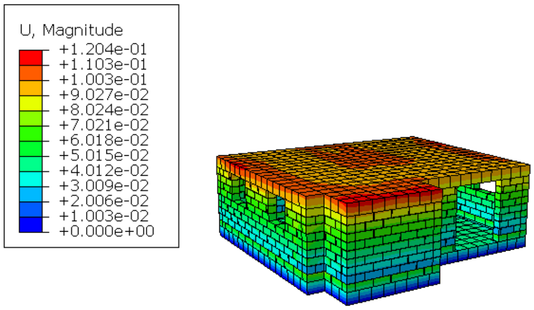


Figure 15. The color contour of the location change created in the 1-story structure model with irregular plan and short floor height in Abaqus software

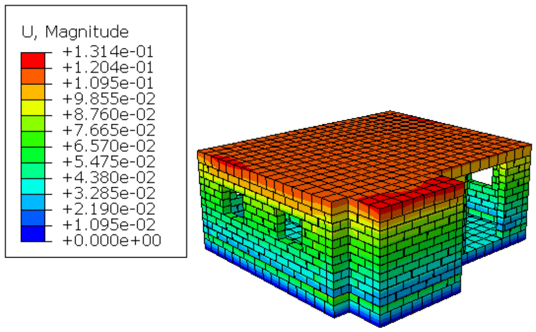


Figure 16- The color contour of the location change created in the model of a 1-story structure with an irregular plan and average floor height in Abaqus software

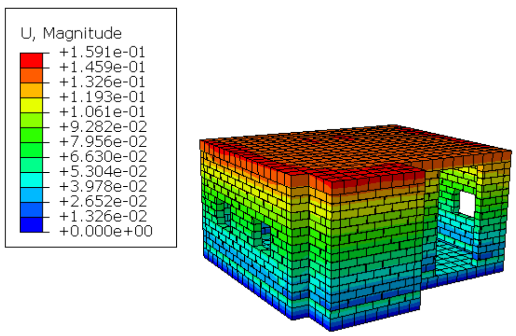


Figure 17. The color contour of the location change created in the 1-story structure model with an irregular plan and high floor height in Abaqus software

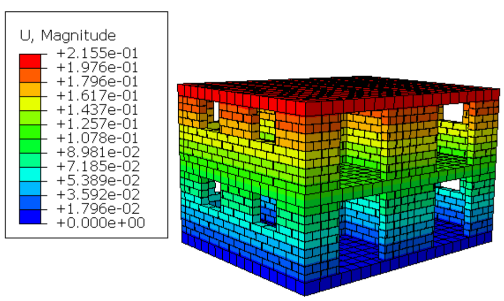


Figure 18. The color contour of the location change created in the 2-story structure model with regular plan and short floor height in Abaqus software

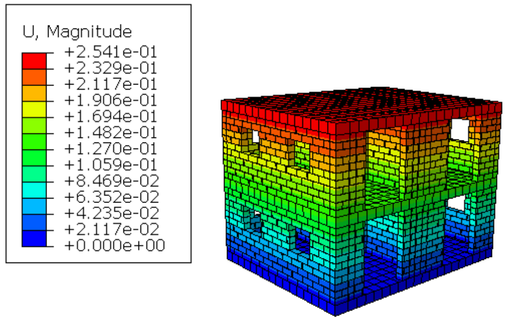


Figure 19. The color contour of the location change created in the 2-story structure model with regular plan and average floor height in Abaqus software

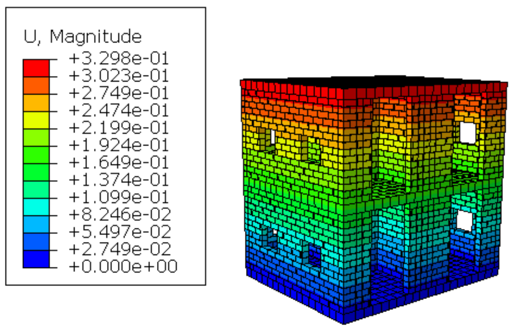


Figure 20. The color contour of the location change created in the 2-story structure model with a regular plan and high floor height in Abaqus software

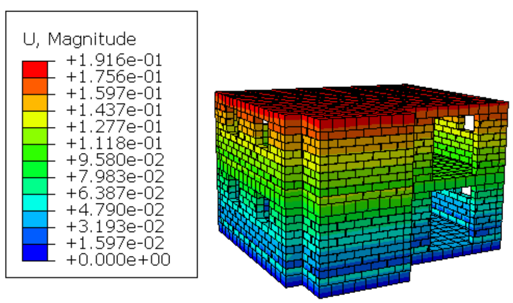


Figure 21- The color contour of the location change created in the 2-story structure model with irregular plan and short floor height in Abaqus software

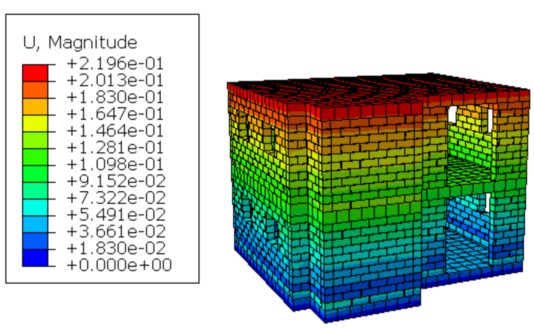


Figure 22. The color contour of the location change created in the 2-story structure model with an irregular plan and average floor height in Abaqus software

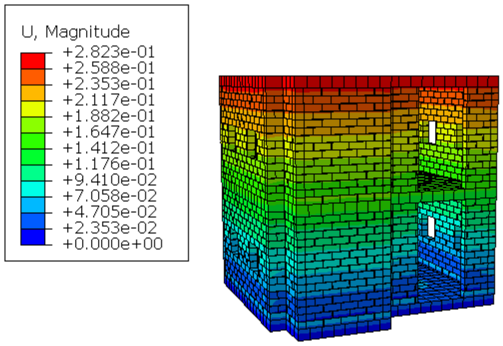


Figure 23. The color contour of the location change created in the 2-story structure model with an irregular plan and high floor height in Abaqus software

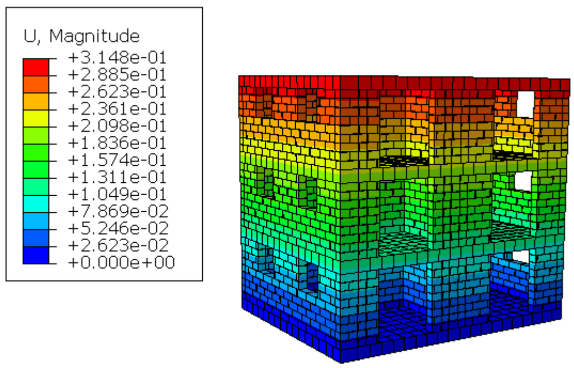


Figure 24. The color contour of the location change created in the 3-story structure model with regular plan and short floor height in Abaqus software

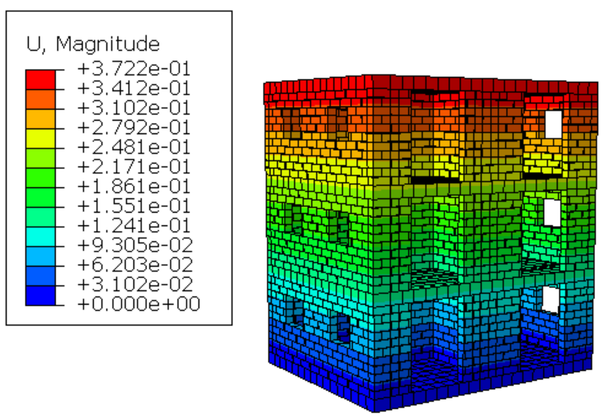


Figure 25. The color contour of the location change created in the 3-story structure model with regular plan and average floor height in Abaqus software

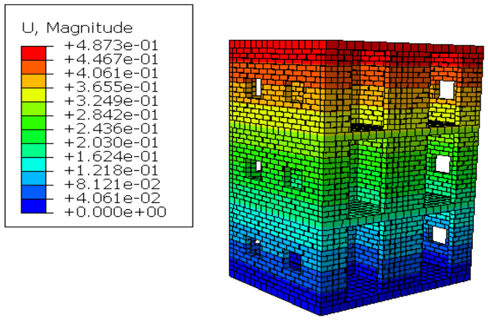


Figure 26. The color contour of the location change created in the 3-story structure model with a regular plan and high floor height in Abaqus software

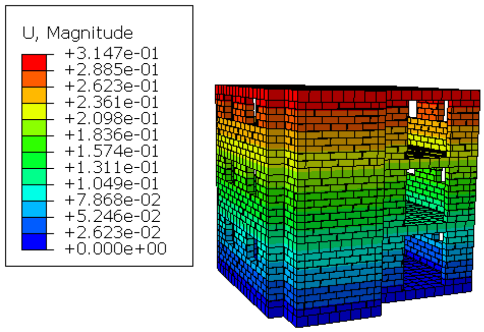


Figure 27. The color contour of the location change created in the 3-story structure model with irregular plan and short floor height in Abaqus software

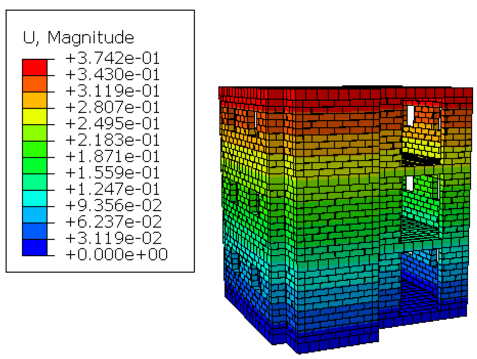


Figure 28. Color contour of the location change created in the 3-story structure model with irregular plan and average floor height in Abaqus software

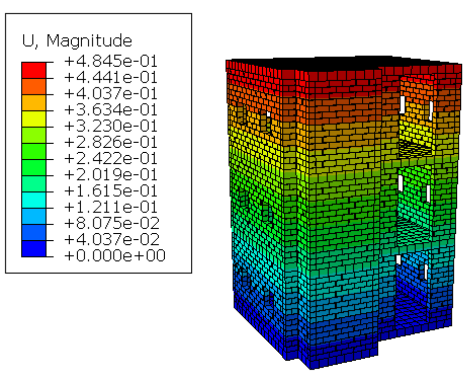


Figure 29. The color contour of the location change created in the 3-story structure model with an irregular plan and high floor height in Abaqus software

- The results of a 1-story structure with a regular plan and a short floor height

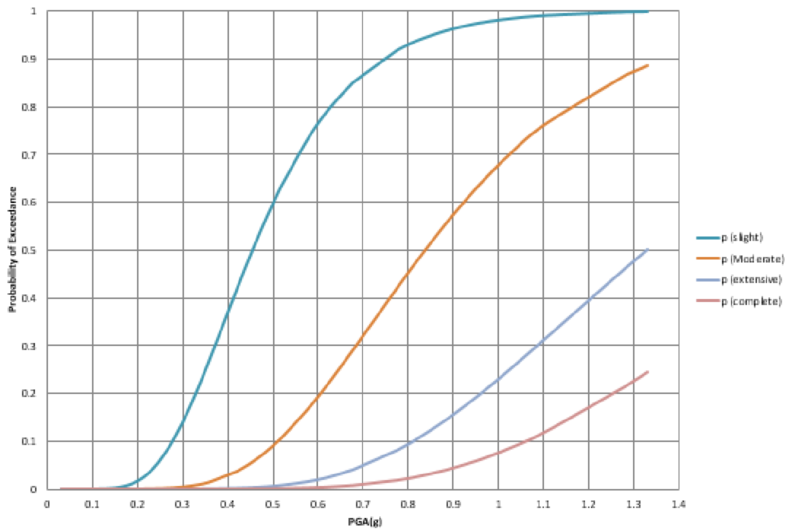


Figure 30. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 88%, 50% and 24%, respectively.

- The results of a 1-story structure with a regular plan and medium floor height

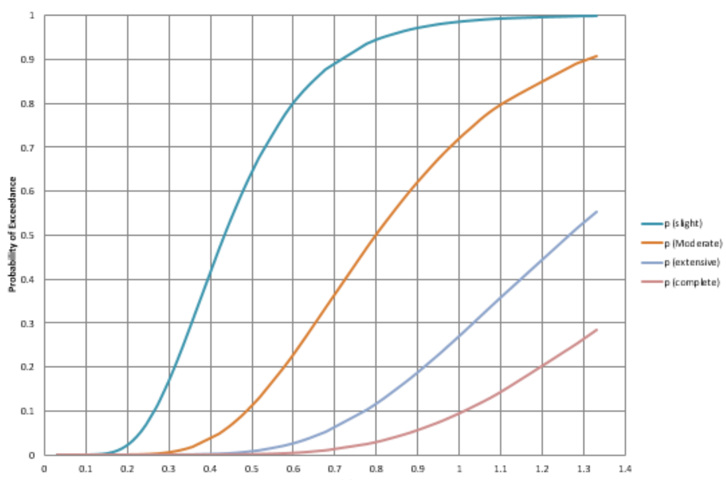


Figure 31- Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 90%, 55% and 28%, respectively.

- The results of a 1-story structure with a regular plan and high floor height

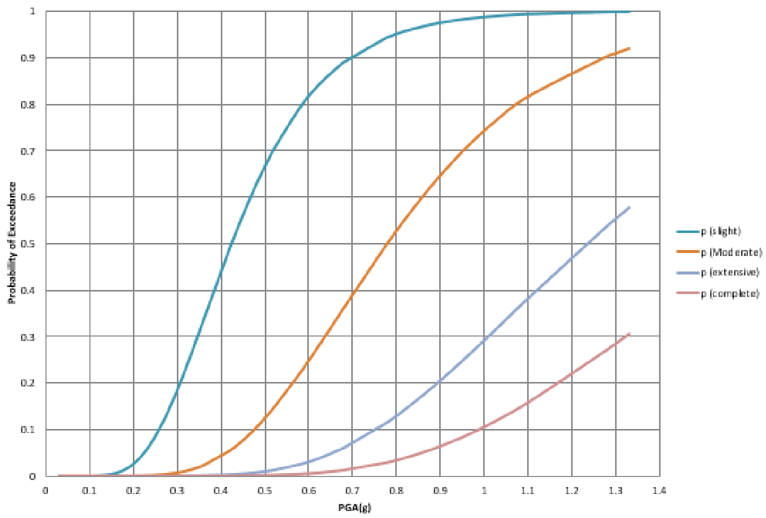


Figure 32. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 92%, 58% and 30%, respectively.

- The results of a 1-story structure with an irregular plan and a short floor height

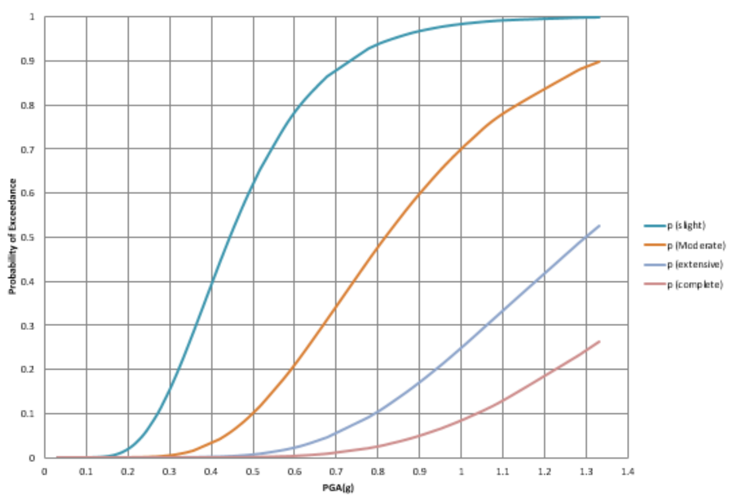


Figure 33. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 90%, 52% and 25%, respectively.

- The results of a 1-story structure with an irregular plan and medium floor height

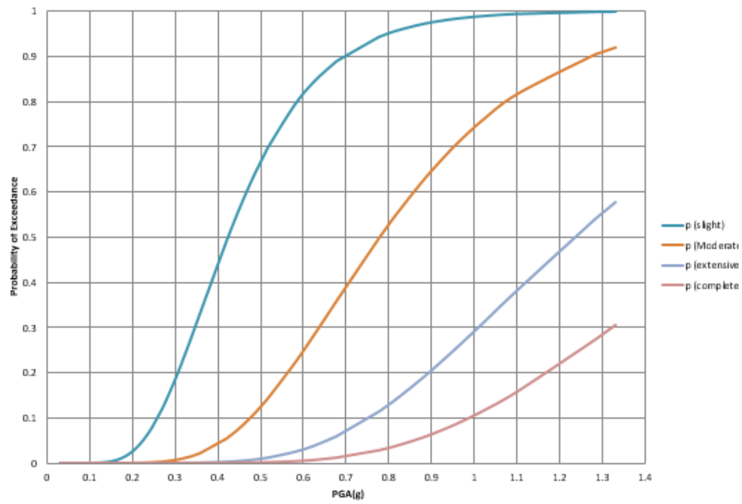


Figure 34. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 92%, 57% and 30%, respectively.

- The results of a 1-story structure with an irregular plan and high floor height

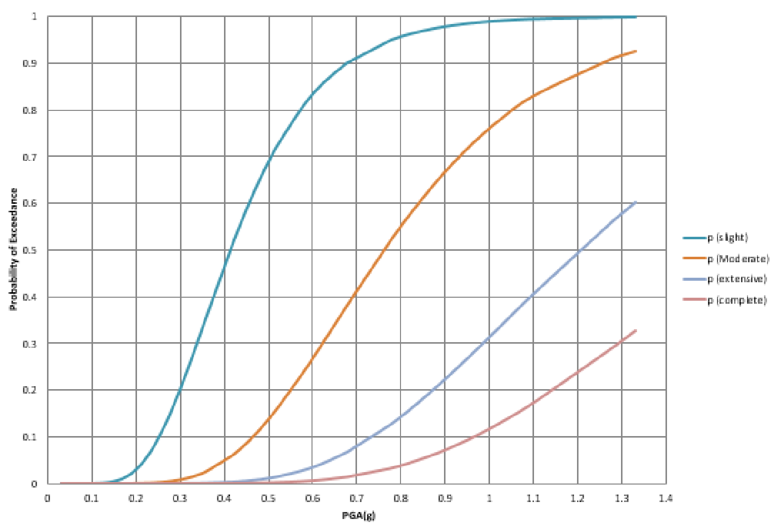


Figure 35. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 93%, 60% and 32%, respectively.

- The results of a 2-story structure with a regular plan and a short floor height

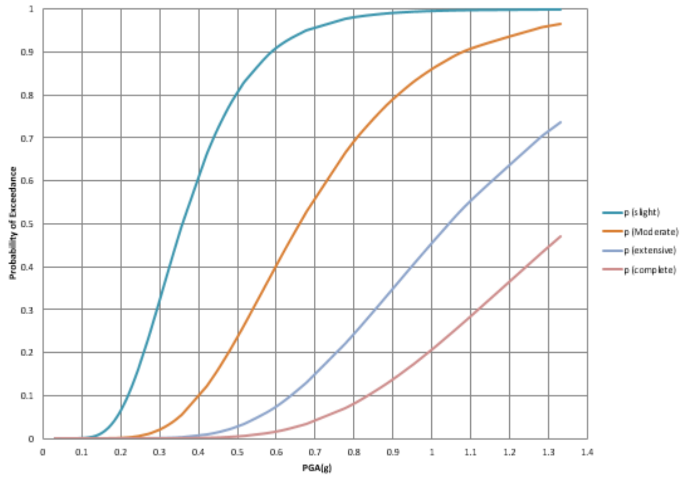


Figure 36. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 96%, 72% and 48%, respectively.

- The results of a 2-story structure with a regular plan and an average floor height

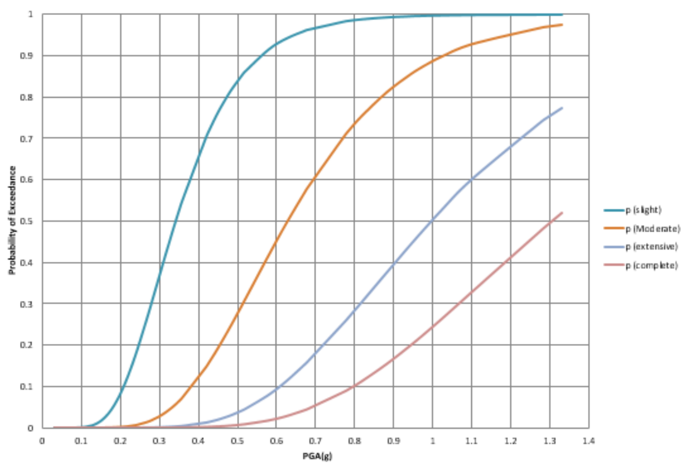


Figure 37. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 97%, 78% and 52%, respectively.

- The results of a 2-story structure with a regular plan and high floor height

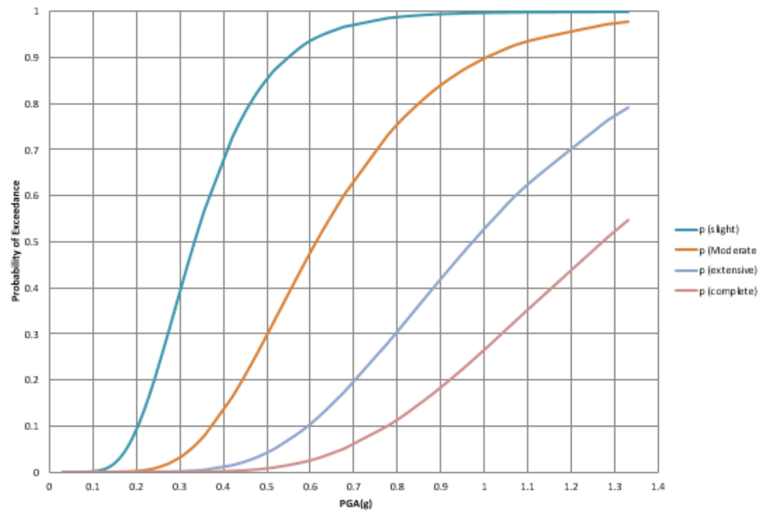


Figure 38. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 98%, 79% and 55%, respectively.

- The results of a 2-story structure with an irregular plan and a short floor height

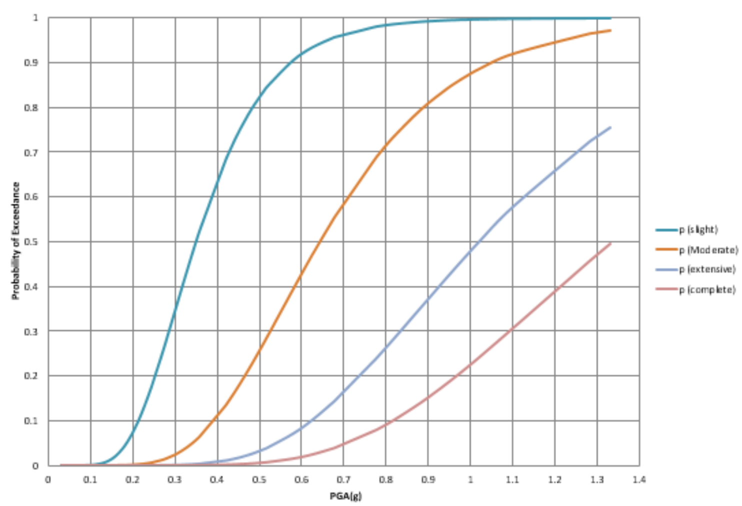


Figure 39. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 97%, 73% and 50%, respectively.

- The results of a 2-story structure with an irregular plan and medium floor height

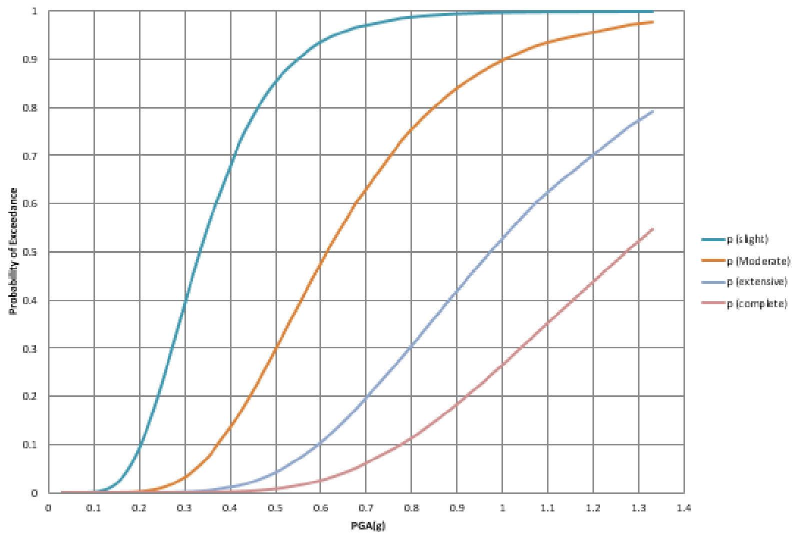


Figure 40. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 98%, 80% and 55%, respectively.

- The results of a 2-story structure with an irregular plan and high floor height

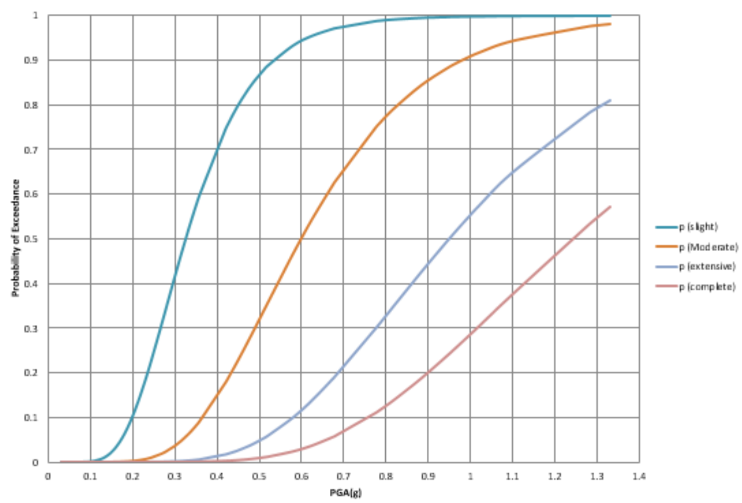


Figure 41. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 99%, 81% and 57%, respectively.

- The results of a 3-story structure with a regular plan and a short floor height

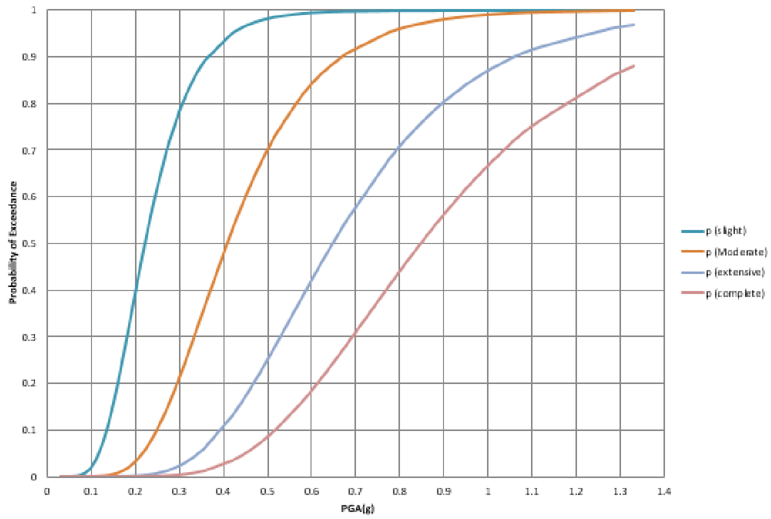


Figure 42. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 100%, 97% and 88%, respectively.

- The results of a 3-story structure with a regular plan and average floor height

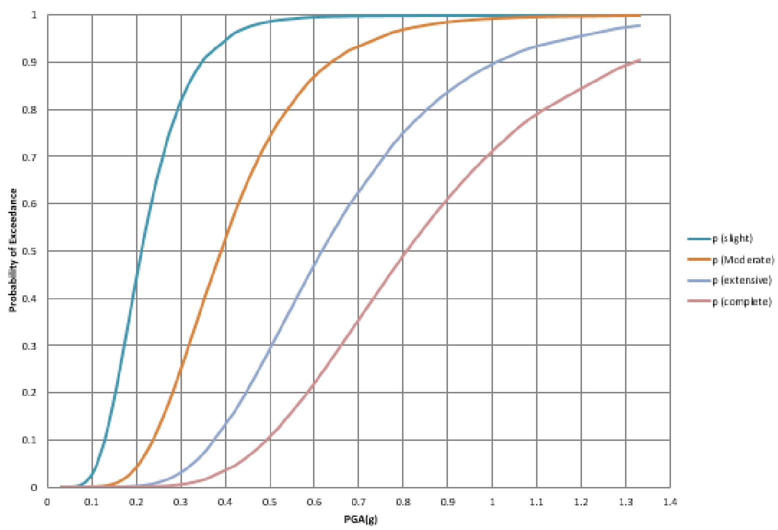


Figure 43. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 100%, 98% and 90%, respectively.

- The results of a 3-story structure with a regular plan and high floor height

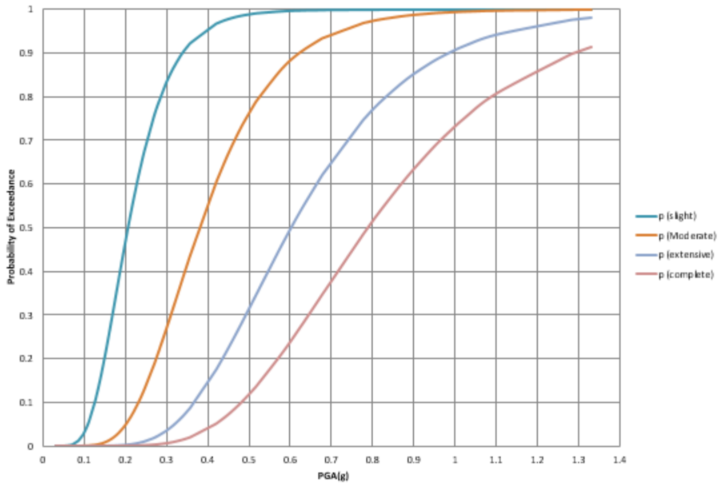


Figure 44. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 100%, 99% and 91%, respectively.

- The results of a 3-story structure with an irregular plan and a short floor height

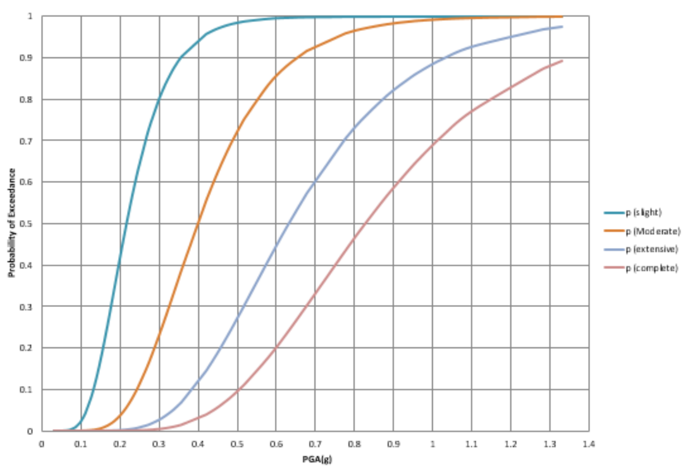


Figure 45. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 100%, 98% and 89%, respectively.

- The results of a 3-story structure with an irregular plan and average floor height

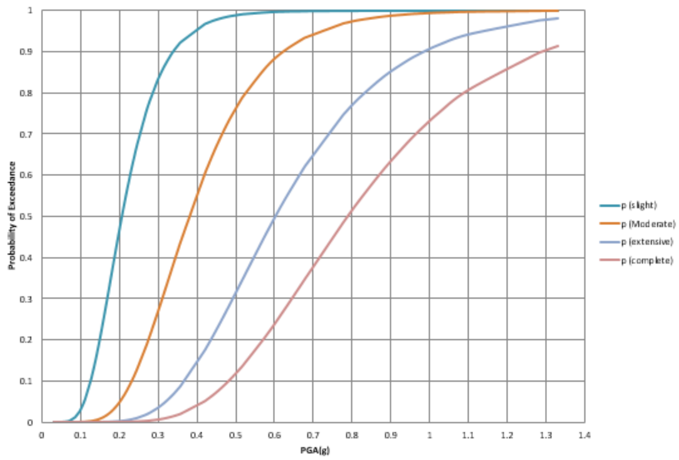


Figure 46. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 100%, 99% and 91%, respectively.

- The results of a 3-story structure with an irregular plan and high floor height

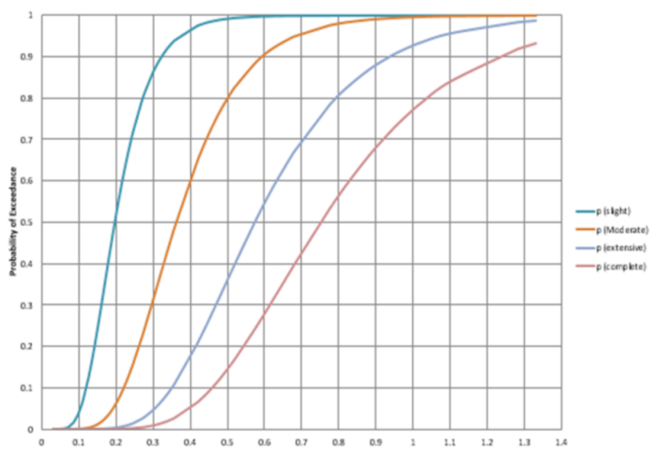


Figure 47. Fragility curve of the structure

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 100%, 100% and 93%, respectively.

4. Conclusion

After examining the principles and basics and modeling based on the principles and logical assumptions of engineering, we have compared the results and the outputs of the software.

According to the available results, we can observe the effects of the number of floors, plan and floor height on the behavior of the structure.

According to the values in the table, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is examined in different states.

1. The exceedance probability of a 1-story structure compared to a 2-story structure from the threshold of slight, moderate, extensive and complete damage has decreased by 59.7%, 94.5%, 99.3%, and 99.8%, respectively.

2. The exceedance probability of a 2-story structure compared to a 3-story structure from the threshold of slight, moderate, extensive and complete damage has decreased by 55.7%, 93.2%, 99.0%, and 99.7%, respectively.

3. By changing the plan of the structure from regular to irregular, the threshold of slight, moderate, extensive and complete damage has increased by 1%, 1%, and 2%, respectively.

4. By changing the floor height from short to average, the threshold of slight, moderate, extensive and complete damage has increased by 1%, 1%, and 2%, respectively.

5. By changing the plan of the structure from average to high, the threshold of slight, moderate, extensive and complete damage has increased by 1%, 1%, and 3%, respectively.

According to the comparison of the results, as the number of floors reduces, we can observe that the percentage of the structural failure threshold is lower.

B. The multi-layer bracing system has increased the formability of the structure.

C. The multi-layer bracing system without considering the soil-structure interaction has reduced the base shear response range. Due to the greater formability of the structure in this bracing system, the structure is more flexible; as a result, less force is applied to the structure.

D. Gravity columns reduce the structural response and thus improve the performance of the structure.

According to the comparison of the models along with the conducted investigations and the obtained results, it is concluded that the use of the multi-layer convergent bracing system has improved the behavior and performance level of the grid structure without considering the soil-structure interaction and the gravity column.

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