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Article

Effects of structural irregularities on the seismic response of a steel structure

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Abstract: Steel structures are commonly used for buildings, bridges, and other infrastructure, due to their high strength-to-weight ratio and versatility. However, the dynamic response of steel structures can be affected by irregularities such as variation in mass, elevation, stiffness, and plan geometry. Therefore, analysis of structural irregularities is important and allows the structural designer to maximize the efficiency of structures in resisting seismic and other dynamic actions. This paper presents a review of the existing methods of analysis of the effects of structural irregularities on the dynamic response of low to medium-high-rise steel buildings. Methods that are used with Eurocode 8 (BS EN 1998:2004) design procedure are discussed. Also, reviewed are the provisions of Eurocode 8, regarding structural irregularity in design, including discussion of the effects of irregularity in mass, elevation, stiffness, and plan. To quantify and compare the effects of different irregularities, SCIA finite element program is used to analyze dynamic response of hypothetical structures with and without irregularities. The computed results of salient deformations and stresses in the structures are compared and discussed, including reference to other researchers' findings. Finally, the implications of various structural irregularities on analysis and design of steel structures are also discussed. The novelty of this research is that it analyses the dynamic response of a predefined structural model, for four types of structural irregularity simultaneously, based on the same control parameters and computational method. Also, even though the use of a building may change at some time, current literature on seismic vulnerability does not adequately address the impact of unexpected changes in mass distribution, but this research does. The findings may help engineers in optimizing design of irregular structures to enhance seismic performance, mitigate risks of seismic damage and promote consistency in design and construction of earthquake resistant structures.

Keywords: code of practice & standards; earthquake; structural dynamics; deformation; finite-element analysis; structural irregularities

1. Introduction

It has long been acknowledged that, when subjected to earthquakes, multi-storey structures of different structural and geometrical configurations are affected differently. Structural irregularity, either in plan or in elevation is identified as one of the major contributors to failure during earthquakes. Additionally, different forms of irregularity may exist in combination and in varying degrees, but the most important ones are irregularities in: (a) plan, (b) elevation, (c) stiffness, and (d) mass. The effects of these irregularities must be considered in design, even though such irregularities may be part and parcel of the functionality and aesthetical requirements of a structure. In view of the above points, an opportunity is taken in this research to study the seismic response of reinforced concrete structures possessing various combinations of irregularities.

Structural dynamics theories and seismic design codes such as BS EN 1998:2004 [1] recognize that structural irregularities in elevation and plan complicate dynamic response and may cause progressive damage or failure of a structure. The problem emanates from higher frequency vibration modes, which become more pronounced as irregularities disrupt the symmetry and uniformity the mass and stiffness distribution in a structure. Higher modes contribute to the overall dynamic response of the structure and can lead to resonant effects, amplifying the building's response to seismic forces. The irregularities may result in localized stress concentrations, increased structural demands, and potential damage in critical regions. Structural irregularity is manifested in unevenness of distribution of mass and stiffness, variations in plan geometry and elevation, and the presence of discontinuities, even if provided by design. It is important to note that real structures are rarely regular, but many codes of practice have guidance on structural irregularity in plan and in elevation. For seismic design purposes, BS EN 1998:2004 [1] specifies the criteria for plan regularity and elevation regularity. Other national codes of practice, e.g., Turkish, give similar specifications and allow the use of "Equivalent Earthquake Load" method, which Burgan [2] implemented in a numerical analysis of a 10-storey irregular (L-shaped plan) building incorporating shear walls. The analysis also considered torsional and stiffness irregularities, in calculating relative storey displacements and second order effects and using the results to recommend the safest and most economical building model.

It should be noted that, other than structural irregularities, seismic response of a structure may also be strongly influenced by ground related factors, e.g., proximity to geological fault lines. Mashhadi et al. [3] performed soil-structure interaction analysis to assess how ground motions near to fault lines influence dynamic behaviour of structures more than ground motions far from fault lines. The analysis was carried out for both regular and set-back structures (irregular in plan) and showed the importance of considering soil-structure interaction for seismically loaded structures where the effects of near-fault pulses are significant.

So far, most experimental studies have concentrated on the effects of irregularities on the elastic response of structures. For dynamic response, researchers have used numerical modelling and computer simulation, however with varying levels of success. In the present work, an opportunity is taken to contribute to knowledge of the dynamic behavior of structurally irregular buildings, by using an advanced numerical analysis and a finite element program, to model structural irregularities. The objectives of the work are to:

(1) to apply the Equivalent Lateral Force method (ELF) and the Modal Response Spectrum (MRS) analyses to determine the stresses and deformations of models of regular and irregular steel structures.

(2) to use the finite element software SCIA [4] to examine how irregularities in mass, elevation, stiffness, and plan influence the dynamic performance of a steel structure.

(3) to formulate possible methods of reducing the negative effects of structural irregularities on the seismic performance of a steel structure.

2. Recent research on structural response to irregularities

Valmundsson and Nau [5] examined effects of irregularities in mass, strength, and stiffness of structures and found that strength irregularity had a greater effect on structural response, compared to mass and stiffness irregularities. This finding is consistent with that of Al-Ali and Krawinkler [6] who investigated the dynamic behaviour of vertically irregular buildings. The authors applied Non-Linear Response History analysis (NL-RHA) method and showed that the effect of strength irregularity on dynamic behaviour was markedly greater than that of mass or stiffness irregularity.

Ansari and Vidhyadhar [7] used structural analysis software to create 3D models of a 12-storey building incorporating irregular distribution in mass. Shear walls were imposed at four corners of each floor plan model, and the effects of uneven masses placed on the 4th, 8th, and 12th floors analysed. Parallel analyses of structural response were carried out for models with and without shear walls but having unequal masses on different floors. The results showed that the effect of a heavy mass at height, on the fundamental vibration period of the structure, decreased by up to 45% due to provision of shear walls at the corners. Furthermore, incorporation of shear walls was found to decrease the structural displacements by up to 35%, in a static analysis, and up to 40% in a dynamic analysis. The study also found that: (i) the maximum storey force occurred at ground floor level, when an RSA was used with an appropriate static analysis, and (ii) the shear at the bottom of the frame structure decreased when mass was re-distributed to higher floors.

With the aid of ETABS [8] and STAAD PRO V8i [9] programs, Mahesh and Rao [10] investigated the response of a tall residential building to earthquake and wind loading. Both static and dynamic analyses were carried out, assuming linearity in material properties. The results showed that the base shear was greater when there were no irregularities than when there were. Mohammadzadeh and Kang [11] also used ABAQUS [12] computer software to examine the effects of plan and elevation irregularities on the seismic performance of a 12-storey steel-frame building 41.6 m tall. In the computer models, whenever there was a flaw in the original blueprint, torsional irregularity was considered. Also, stiffness irregularity was included whenever there was a height discrepancy in the models when compared with the blueprint. The program ABAQUS [12] was used to perform non-linear incremental dynamic analysis, based on a time histories obtained from actual seismic records from past earthquakes in Vrancea County, Southeast of Romania. The study found that:

- Mass inequalities between different storeys caused the height location of the maximum storey drift to vary in response.
- With increasing stiffness irregularity of storeys, the residual drift increased more markedly than in a regular structure.
- A regular structural configuration had a considerably better response to earthquake loading and deformed less than the irregular building.

Varadharajan et al. [13] carried out numerical analysis of seismic response of multistorey reinforced concrete frame with vertical mass and stiffness irregularities. This was by building models with different types of irregularity with variation in magnitude and location of irregularity. These were then subjected to 27 ground motions to create a seismic response dataset. Torsional effects induced by irregularities were considered, following the recommendations of BS EN 1998:2004 [1]. Based on regression analysis on the response dataset, equations were proposed for estimating seismic response parameters, e.g., fundamental period, maximum roof displacement and maximum inter-storey drift ratio.

Tremblay et al. [14] sed the equivalent static analysis and dynamic analysis methods described in the National Building Code of Canada [15] for 4, 8, 12 and 16 storey buildings that have structural mass irregularity. Elevation setbacks required to cause mass discontinuities of 200% and 300% were positioned at heights of 25%, 50% or 75% of the height of the building. The results showed that the storey shear forces, overturning moments, and storey drifts obtained from static analysis were higher than those from a dynamic analysis method.

Le-Trung et al. [16] investigated the effects of different types of structural irregularity (i.e., mass, stiffness, and strength irregularity) on the seismic behaviour of 24 steel special moment framed buildings in Los Angeles, USA. The buildings were subjected to 20 earthquake ground motions and nonlinear static and dynamic analyses performed. Calculations of the height-wise distribution of storey drifts, maximum storey drift demands, global collapse, storey drift capacities and confidence levels were performed. It was concluded that the greatest effect on seismic behaviour was strength irregularities of a building.

Shojaei et al. [17] carried out dynamic non-linear analysis to compute damage indices on cases of 3 storey reinforced concrete buildings with and without irregularities and subjected to specified earthquake loading. It was found that a structure with soft story irregularity sustains more damage under earthquake than one without.

Mohamed and Elmokhtar [18] investigated the effects of soil site classes (S1—hard rock, S2—very dense soil, S3—stiff soil, S4—soft soil) on the structural vulnerability of irregular reinforced concrete buildings under earthquake action. Based on non-linear pushover analysis, fragility curves were developed, and it was demonstrated that site class significantly affects the seismic vulnerability of buildings. It was also shown that the building’s fragility is sensitive to the location of geometric irregularities.

Sekhar et al. [19] carried out response spectral and non-linear time history analyses on several case studies of buildings having different irregularity configurations. It was found that irregular structures exhibit less base shear but cause higher stress concentration and ductility demand in the members around the irregularity. Thus, it was suggested that the seismic performance of irregular buildings could be improved by increasing strength of structural elements in the vicinity of vertical irregularity.

In summarizing, researchers generally agree on the importance of structural regularity to the unfavorable effects of dynamic actions. Opinions only vary regarding quantification of the individual effects of the various irregularities (mass, stiffness, elevation geometry, plan geometry) on dynamic load response of the structure. There are useful recommendations in BS EN 1998:2004 [1] however these mainly focus on the criteria for regularity, without specific guidance on how to mitigate the unwanted effects of irregularity on seismic performance.

3. Methodology of analysis

3.1. Preamble

Seismic analysis was carried out for a hypothetical building comprising a moment resisting steel frame and concentrically braced frames. The building was 28 m high G + 7 (ground floor plus seven other floors) and was modelled with SCIA [4] finite element analysis program. According to BS EN 1998:2004 [1], the building classified as a high-rise since it was greater than 25 m in height. Analyses were carried out for both regular and irregular configurations of the building. In the models, irregularities were defined as inequalities of plan, mass, elevation, and stiffness between different floors. The regular building served as the reference for comparison of the effects of irregularities on dynamic performance. The analysis method is general, hence not confined to the structural shapes and sizes in this paper, but valid for any 3D framed structure. The work was part of a research carried out by Chhetri [20] at Kingston University, London, UK.

In the analysis of the regular structure models, the following parameters were kept constant: the bay area, number of storeys, damping ratio, frequency, and height of building. The same was done for the irregular structure models, except for the model that had elevation irregularity. In this model, the height of the 5th floor was increased to 5.6 m while for the other floors the heights were decreased to 3.2 m, thus keeping the building height unchanged.

3.2. Regular building model

The model had the floor plan shown in **Figure 1** and uniform storey heights of 3.5 m as shown in **Figure 2**. The 31 m by 31 m floor plan had 5 bays in each direction {x, y}, and symmetrical along both directions.

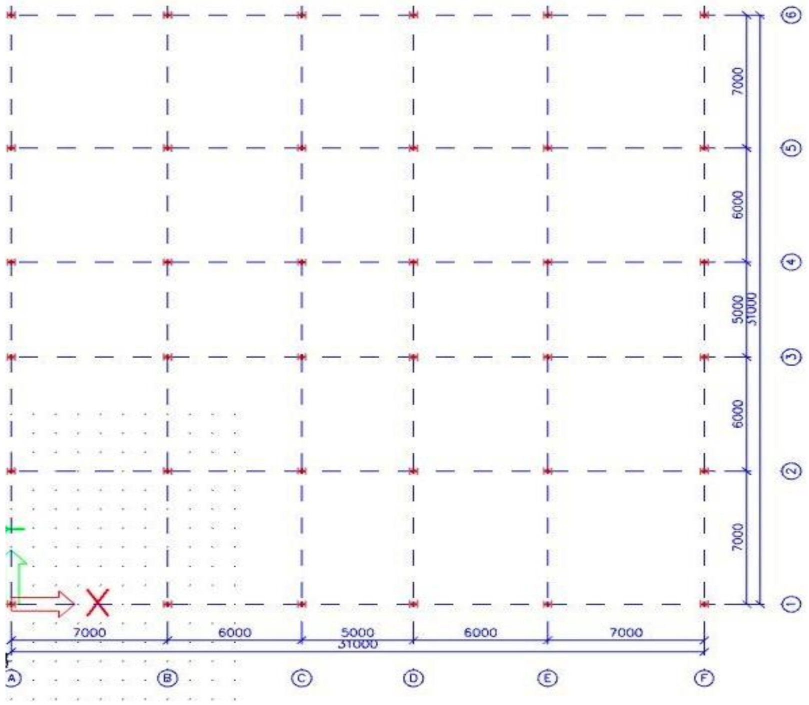


Figure 1. Plan of structurally regular building model.

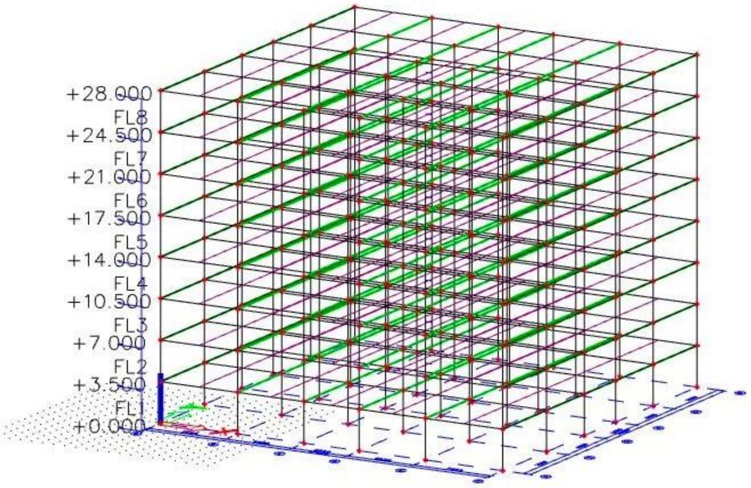


Figure 2. Schematic 3D model of the regular building.

3.3. Irregular building model

Plan irregularity: Structures with irregularities in plan or in elevation present special ductility demands in certain locations contrary to the general demand of uniform ductility distribution in normal buildings. Structures that are regular in plan tend to respond to seismic excitation along their main structural directions in an uncoupled manner. In such a case, the structure can be analyzed in a simplified way, using planar models in each main structural direction. Contrastingly, plan irregularity has a strong influence on the torsional irregularity of the building model. A building can be characterized as regular in plan if it meets all conditions in Clause 4.2.3.2 (I) of BS EN 1998:2004 [1], for all storey levels. In the present analysis, an L-shaped plan (**Figure 3**) with the same floor area 31 m × 31 m was modelled for dynamic response.

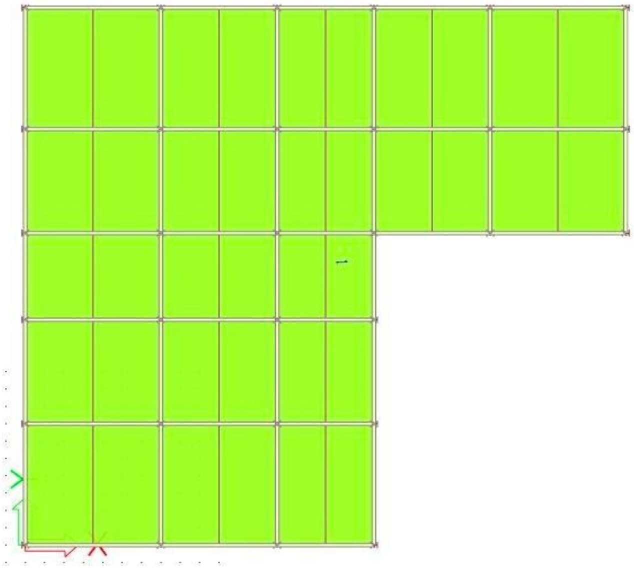


Figure 3. Model with plan irregularity (L-shaped) only.

The resulting torsional irregularity emanates from disparities in the centre of gravity and rigidity of the structure, from one floor to another. The ununiform centres of gravity cause torsional moments hence shear forces in the columns. Ideally, lateral loads induced by earthquake or wind gusts should be transferred from the floor slabs to the columns and shear walls, for optimum stability. Despite the common assumption that floor slabs have an infinite in-plane rigidity, a large opening in a slab can significantly change the rigidity of the slab and consequently alter the distribution of lateral loads, thereby influencing the seismic response of the structure. Any lateral displacements will impose additional shear stresses on the columns.

Elevation irregularity: Elevation irregularity in a structure is expected to have a more severe effect on the seismic response compared to plan irregularity. Clause 4.2.3.3 of BS EN 1998:2004 [1] defines the conditions that must be met for a building to be classified as regular in elevation. For such a case, static analysis with equivalent horizontal seismic loads, can be used, provided the basic period of the structure in the two main directions is within the limit defined in Clause 4.2.3.3. of BS EN 1998:2004 [1]. Where there is elevation irregularity, the behavior factor q is reduced by 20% in comparison with the case of regular elevation. The study considered elevation irregularities associated with storey height disparities. Here, the height of each floor was reduced to 3.2 m from 3.5m except for the 5th floor, which was kept at 5.6 m (**Figure 4**). The total height of the model building was therefore the same as it was for the regular structure model.

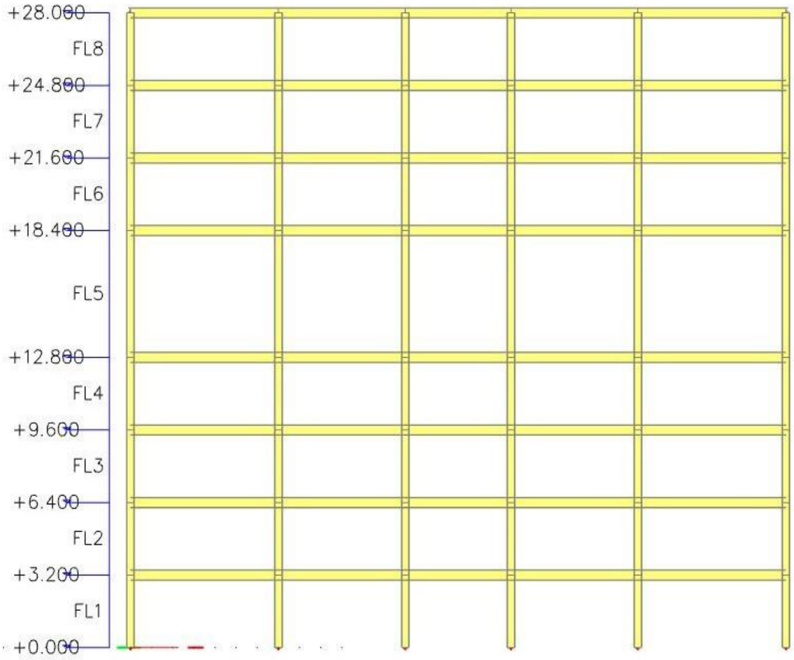


Figure 4. Model with elevation irregularity only.

Mass irregularity: For this case, loading was increased on 5th floor by doubling both dead load and live load (**Figure 5**). All other parameters were kept the same as in the regular structural model.

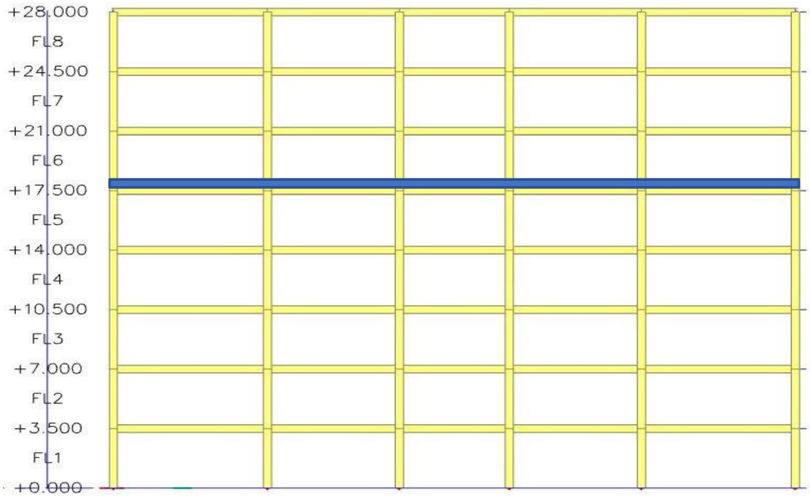


Figure 5. Model with mass irregularity only.

Stiffness irregularity: Here, bracings were introduced as concentrically braced frame (**Figures 6** and **7**) while also specifying smaller size of the column along the *Y*-axis (columns 2-2 f-f, 3-3 f-f, 4-4 f-f, 5-5 f-f, 2-2 A-A, 3-3 A-A, 4-4 A-A, and 5-5 A-A).

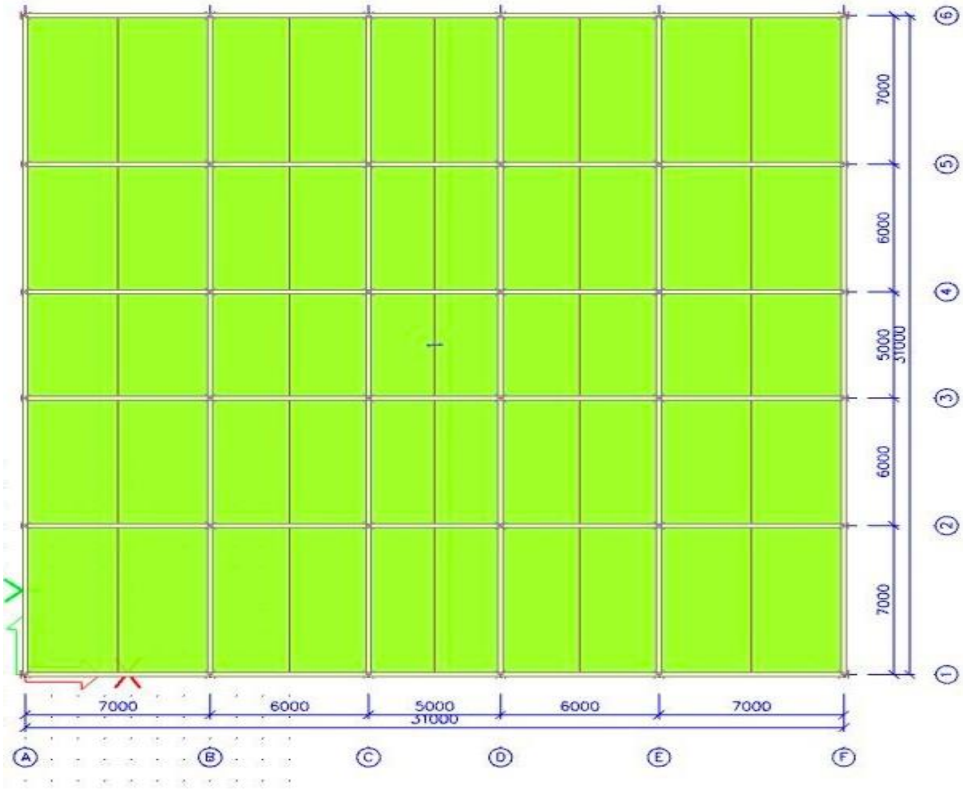


Figure 6. Model with stiffness irregularity only (plan view).

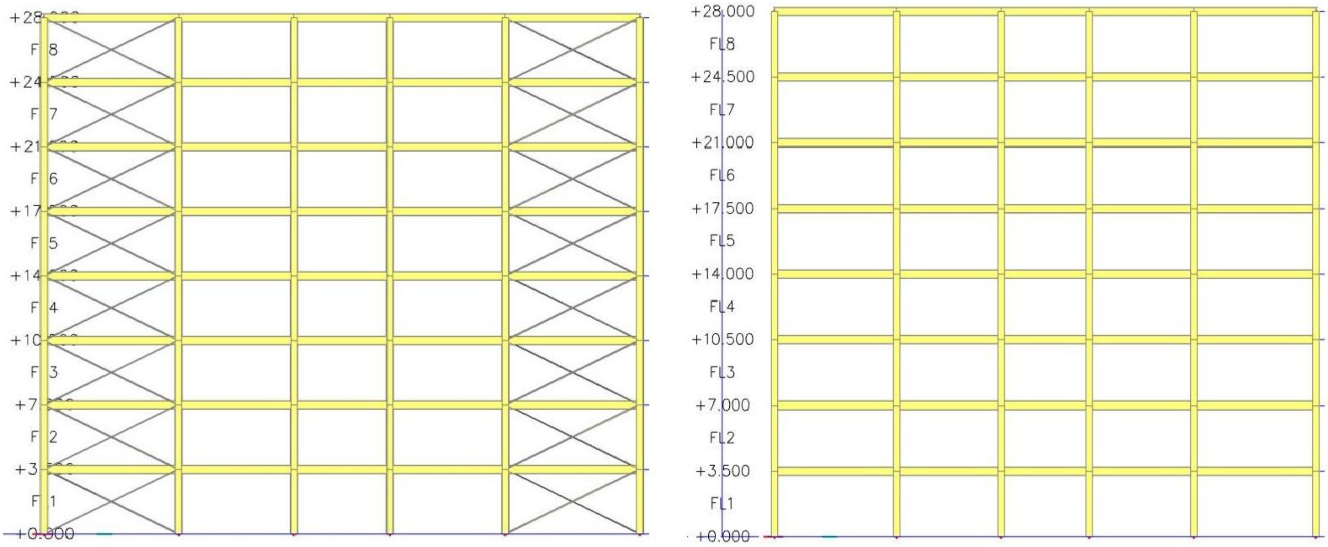


Figure 7. Model with stiffness irregularity (elevations through *Y* and *X* axes).

3.4. Finite element analysis of the models

Based on the recommendations in BS EN 1998:2004 [1], ELF and MRS analysis methods were performed in SCIA [4] for both the regular and irregular models. The objective was to discover what differences there could be in the dynamic behaviour of the regular and the irregular models, under the same specified loading conditions.

Model details: Five different models were created in SCIA [4], including one regular and four variously irregular models. The irregularities were in plan, elevation, mass, and stiffness.

Geometry: To formulate an appropriate finite element model (FEM), the following settings were defined:

- Analysis type—dynamic and seismic spectral analysis.
- Created geometry line grids and structure storeys, for the 5 models (1 regular and 4 irregular).
- Selected cross-sections from the SCIA [4] libraries and assigned to relevant grids.
- Assigned load cases and combinations of loads.
- Launched SCIA [4] program for the 10 eigenmodes and checked for the modal mass contribution.

Material properties—Structural steel grade S275 material properties for the beams, columns, and X-bracings. For columns and beams, I-sections were defined and X-bracings L-sections were used (**Figure 8**).

The section dimensions were as follows:

Column 1: UC 356/368/177 where t_w = 14.5, Second moment of the area through axis y-y = 57,200 cm^4.

Column 2: UC 305/305/118 where t_w = 11.9, Second moment of the area through axis y-y = 9010 cm^4.

Beam: UB457/191/174 where t_w = 9.1, Second moment of the area through axis y-y = 1670 cm^4.

X-Bracing: RSEA50/50/5.

For the panel, a load panel with edge and beam was specified.

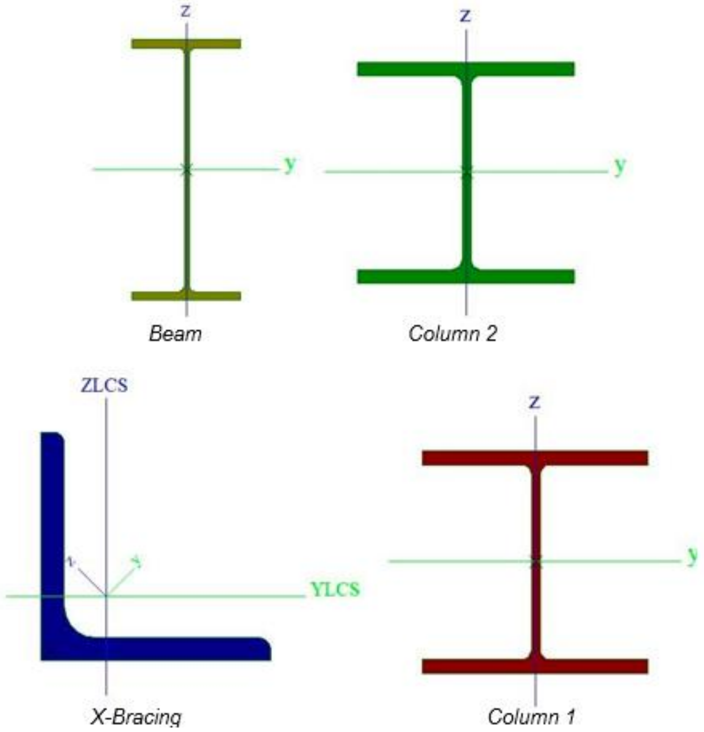


Figure 8. Cross-sections of the steel elements in models.

3.5. Loading configuration and boundary conditions

For floors and roof, dead loads were taken as 4 kN/m^2 while live loads were 3 kN/m^2. These values were applied to all models except the model having mass irregularity, where the dead and live loads were assigned as 8 kN/m^2 and 6 kN/m^2 respectively.

For seismic actions, loadings were assigned according to BS EN 1998:2004 [1], assuming:

- Site location to be Zone 4 (e.g., West coast of Wales, UK).
- PGA = 0.17 g (based on British Geological Survey [21] map of West Wales, UK).
- Ground type = C.
- Importance factor = 1.
- Behaviour factor q = 4.
- Elastic response spectra = Type 2, for low seismicity (**Figure 9**).
- Surface-wave magnitude assumed less than 5.5.
- Damping ratio = 5%.

Values of the various parameters defining Type 2 elastic response, interpreted from BS EN 1998: 2004 [1], are shown in **Table 1**.

For the behaviour factor, q, moderate ductility class (DCM) was adopted for the low seismicity UK site assumed. According to BS EN 1998:2004 [1], the behaviour factor varies according to the ductility class and whether the structure is regular or irregular. For a regular DCM structure, $q = 4$ for multi-bay, multi-storey buildings and the same for the diagonal bracings. For a high ductility class (DCH), $q = 6.5$ for multi bay-multi storey buildings and $q = 4$ for the diagonal bracings. For an irregular DCM structure, $q = 3.2$ for multi-bay, multi-storey buildings. The same values apply to diagonal bracings, but for a structure that is irregular in elevation only.

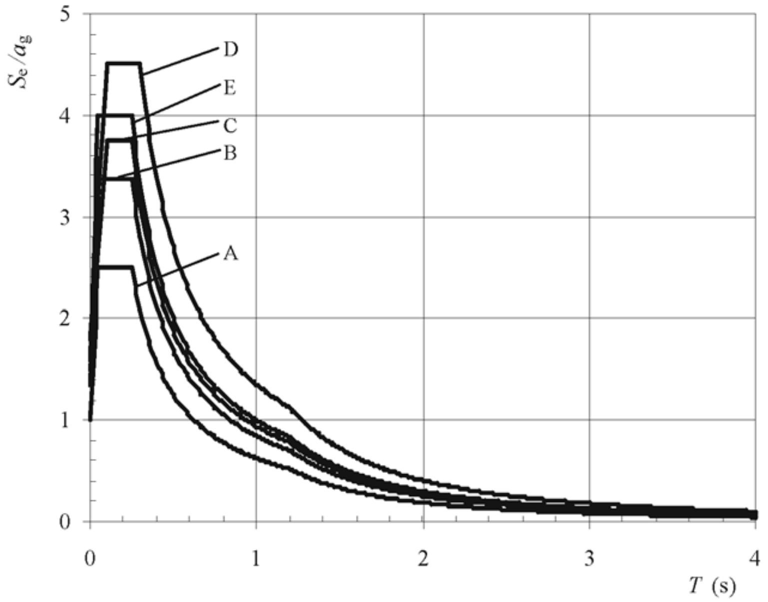


Figure 9. Adopted elastic response spectra (Type 2) for ground types A to E (with 5% damping)—from BS EN 1998:2004 [1].

Table 1. Values of the parameters describing the Type 2 elastic response spectrum.

Ground type	S	T_b (s)	T_c (s)	T_d (s)
A	1.0	0.05	0.25	1.2
B	1.35	0.05	0.25	1.2
C	1.5	0.10	0.25	1.2
D	1.8	0.10	0.30	1.2
E	1.6	0.05	0.25	1.2

3.6. Analysis procedure

For the dynamic analysis of the regular and the irregular models, the modal response under static load and eigen modal mass, so that the period and mass participation of the structure are satisfied. From the calculation protocol, an output of the solution of free vibration for 10 eigen modes was obtained from SCIA [4], each mode having its values of period, frequency, and other parameter values. It was found that the period for mode 1 was 0.54, and for mode 2 it was 0.50. The total mass participation was 81.19%, which needed improvement, hence it was advantageous to use the improved reduced system (IRS) in SCIA [4]. This made it possible to consider not only the stiffness matrix of the system, but also the mass matrix, during the reduction process. The IRS system helps to eliminate local modes, leads to better convergence of the modal mass, hence produces excellent results in dynamic analysis. The IRS function was therefore activated in the solver settings within SCIA [4], for all storeys of the structure models. On displaying the outputs from the revised calculation protocol, with IRS activated, the total mass contribution increased to 94.81% and, for mode 2 the period decreased by 1 s while for mode 10 the values were much different from the results in the previous analysis done without IRS use.

Both the equivalent lateral force (ELF) method and the response spectrum (MRS) methods were used in the analyses. The ELF method was applied in cases where the structural models satisfied the criteria in BS EN 1998:2004 [1]. These are regularity in elevation, integrity of the structure in resisting lateral loads, regular vertical distribution of masses, basic vibration period in two important directions meeting the requirements of BS EN 1998:2004 [1].

The structural models that did not satisfy the requirements for the ELF method were checked against the following requirements of BS EN 1998:2004 [1]. (a) at least 90% of the overall mass of the structure can be accounted for by the sum of the effective modal masses for the modes that were studied, (b) all modes are considered if their effective modal masses account for more than 5% of the overall mass.

Modal mass was considered in the analysis in one of the 3 different ways: (i) participating mass only, where the calculated modes are considered sufficient only when the total modal mass ratio was greater than 90%, (ii) missing mass in modes, where the results obtained from the calculated modes were amplified to compensate for the lack of modal mass ratio, and (iii) residual mode, where the missing masses were associated with rigid parts of the structures and were therefore not in vibration but subjected to ground acceleration as rigid bodies. Lastly, the pseudo-mode was computed and included in modal superposition. In accordance with BS EN 1998:2004 [1], to compensate for mass distribution irregularities and seismic motion variations in space, accidental torsion was automatically considered within SCIA [4], at each floor of the structure. This was done by imposing additional eccentricity of storey mass equal to 5% of the floor dimension perpendicular to the direction of the Seismic action.

In the SCIA [4] program, the IRS method allows consideration of not only the stiffness matrix of the system, but also the mass matrix during the condensation process. This method has been found to give excellent results for dynamic analysis, with both modal analysis and direct time integration methods. The SCIA [4] IRS algorithm consists of 3 steps: (a) using IRS to condense the model mesh, (b) performing the modal analysis using the reduced mesh, with typically 1000 times less degrees of freedom than the original full mesh. This accelerates the calculation of eigenvalues hence saves time in analysing large structures, (c) expanding the results of the reduced system to the original full mesh, allowing for output of detailed results in the entire structure.

Before using the IRS method, the seismic calculation process is completed first, as described in the flow chart in **Figure 10**.

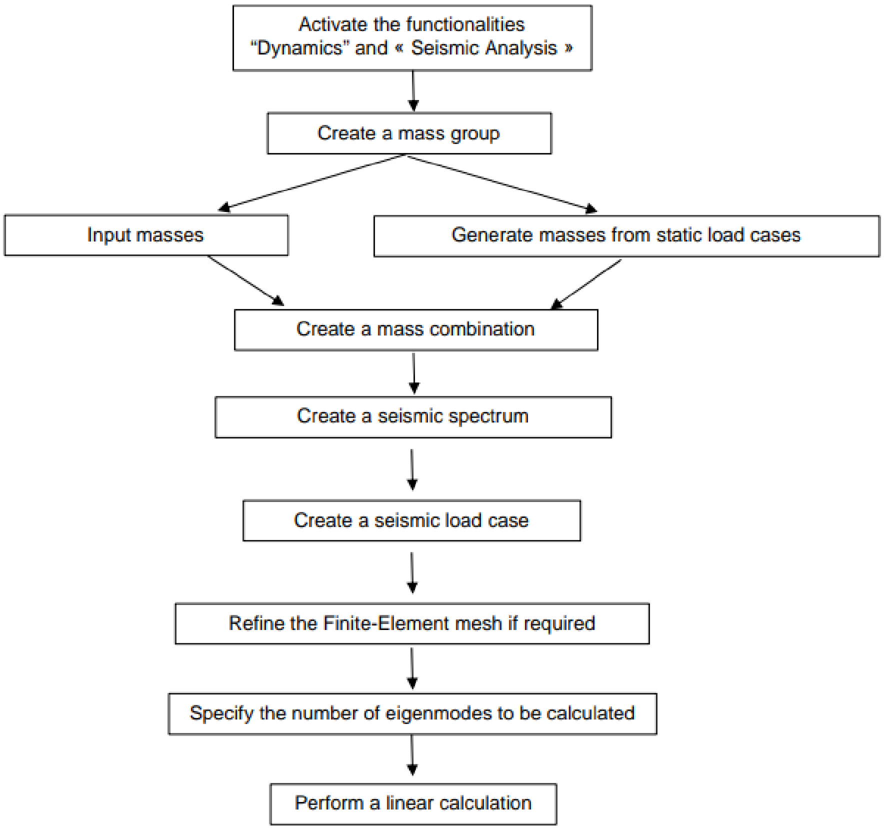


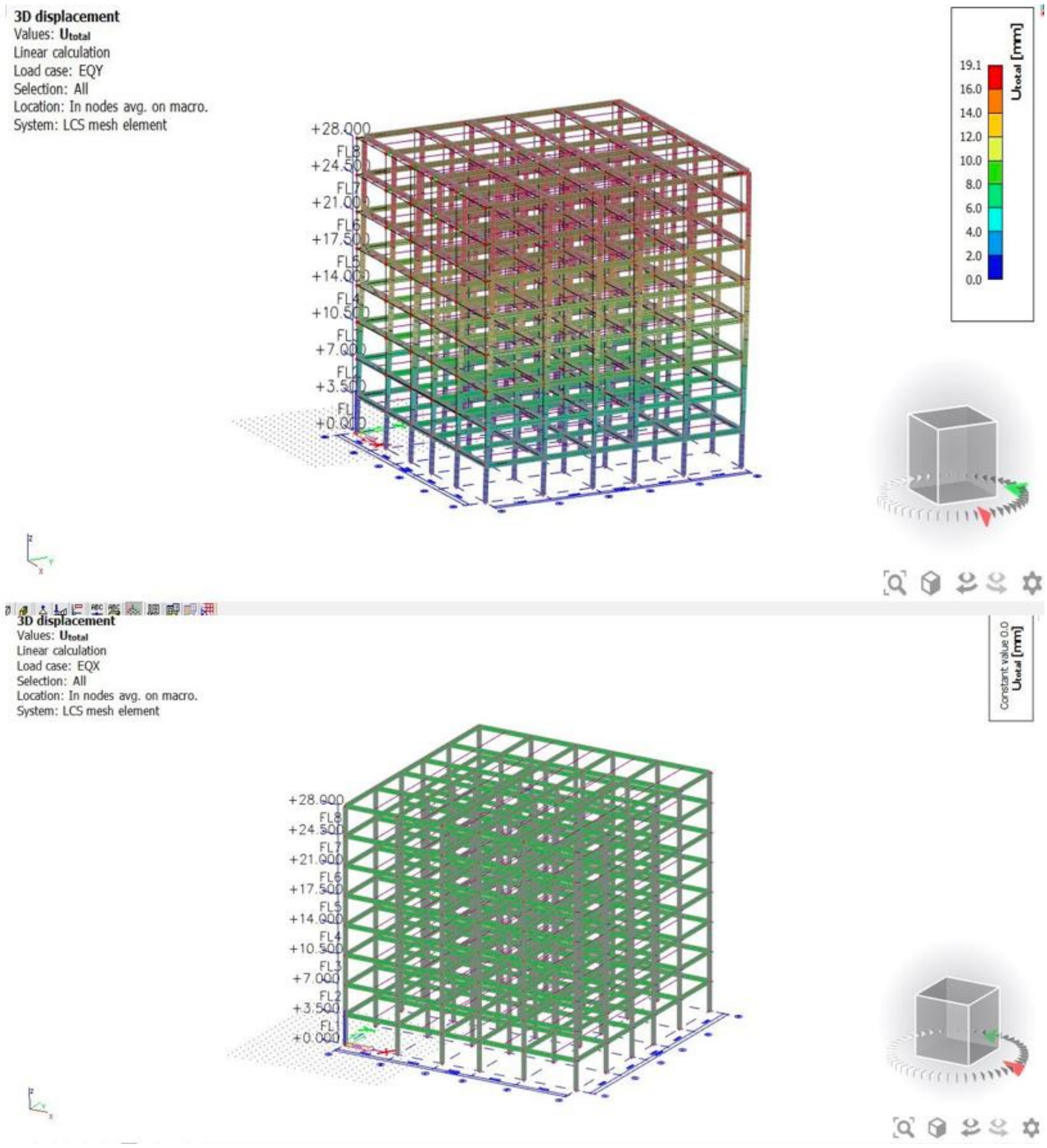
Figure 10. SCIA spectral analysis process flowchart.

4. Results of analyses and discussion

4.1. Regular structure

Figure 11 (load cases: top diagram is EQY, and bottom is EQX) are the computed 3D displacements, for the regular structure. Here, the ELF method was used for analysis as it satisfied the required conditions for validity of the ELF method. The analysis included IRS refinement, which gave the improved total mass contribution of 94.81%. Since the building plan was regular, with the defined structural elements being I-sections, the deformed shape on the *X*-axis was zero EQX load cases but for the *Y*-axis the extreme displacement was calculated to be 19.1 mm for the load case EQY.

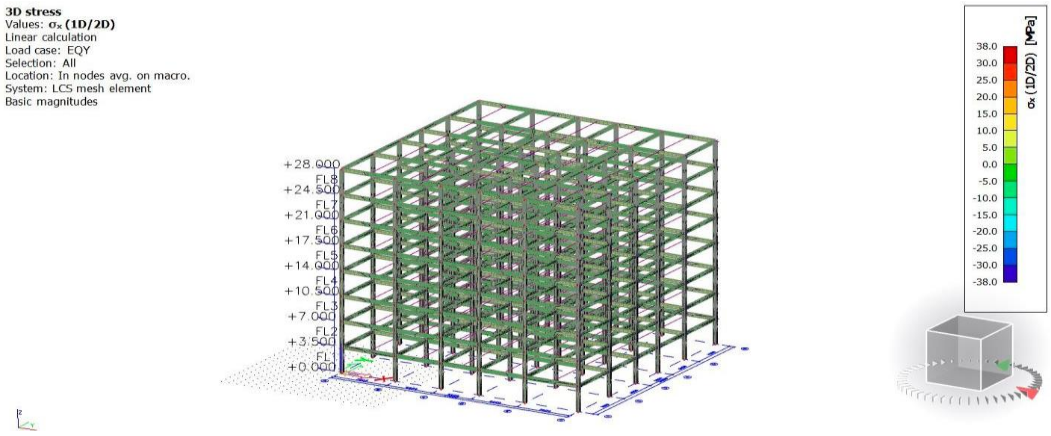
The 3D stresses computed for the regular structure are illustrated in **Figure 12**. It was found that the maximum stresses were −38.0 MPa and 38.0 MPa and occurred in column grids C21 and C15.



3D displacement
Values: U_{total}
Linear calculation
Load case: EQY
Selection: All
Location: In nodes avg. on macro.
System: LCS mesh element

3D displacement
Values: U_{total}
Linear calculation
Load case: EQX
Selection: All
Location: In nodes avg. on macro.
System: LCS mesh element

Figure 11. Displacements (regular structure).

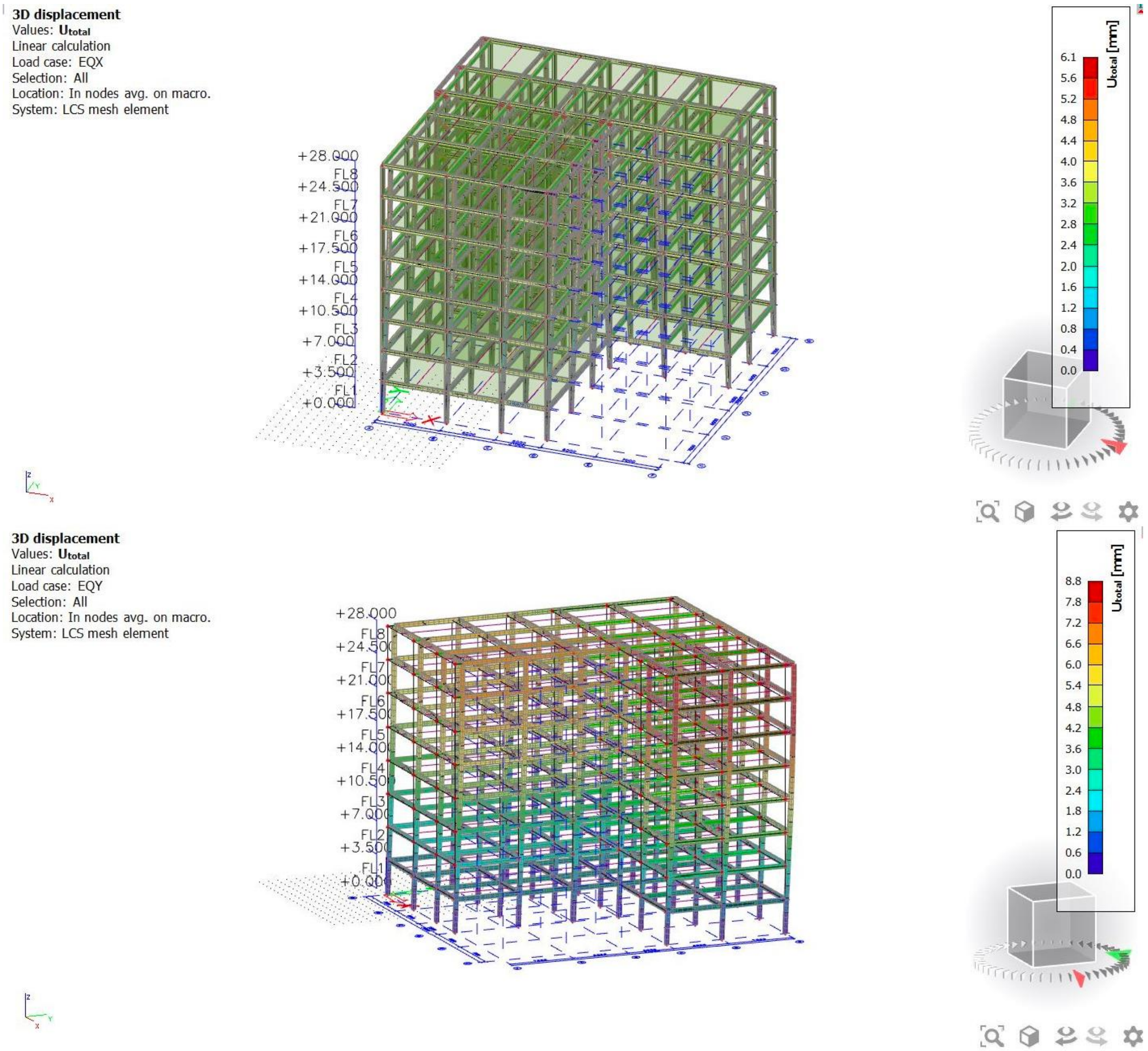


3D stress
Values: σ_x (1D/2D)
Linear calculation
Load case: EQY
Selection: All
Location: In nodes avg. on macro.
System: LCS mesh element
Basic magnitudes

Figure 12. Stresses for EQY load case (regular structure).

4.2. Structure with plan irregularity

Figure 13 shows the 3D displacements, under the seismic load cases EQX and EQY. These resulted from the modal response spectrum analysis. The plan irregularity induced torsional irregularities. It was found that for the EQX load case, the maximum displacement was 6.1 mm whereas for EQY the displacement was up to 8.8 mm.



3D displacement
Values: Utotal
Linear calculation
Load case: EQX
Selection: All
Location: In nodes avg. on macro.
System: LCS mesh element

3D displacement
Values: Utotal
Linear calculation
Load case: EQY
Selection: All
Location: In nodes avg. on macro.
System: LCS mesh element

Figure 13. Displacements in EQX and EQY cases (plan irregularity).

The 3D stress results are shown in **Figures 14** and **15**, for the seismic loading in case EQX and EQX respectively. It was found that column grid C66 experienced the maximum stresses of −16.5 MPa and 16.1 MPa and beam B73 had the maximum stresses of −12.1 MPa and 12.2 MPa respectively.

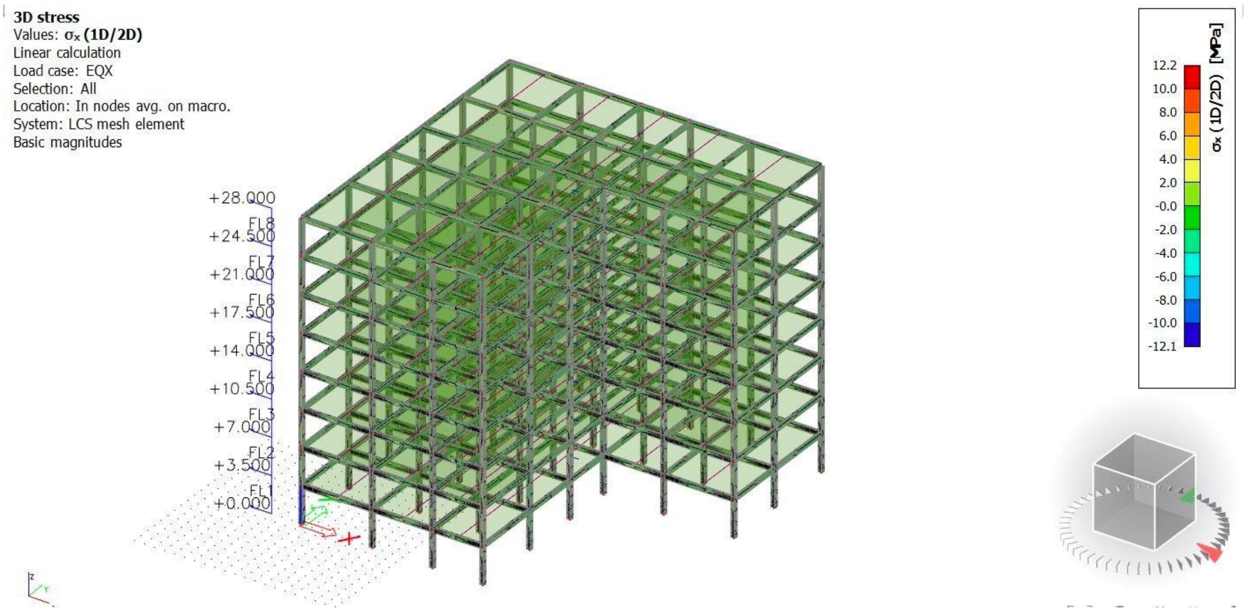


Figure 14. Stresses under EQX load case (plan irregularity).

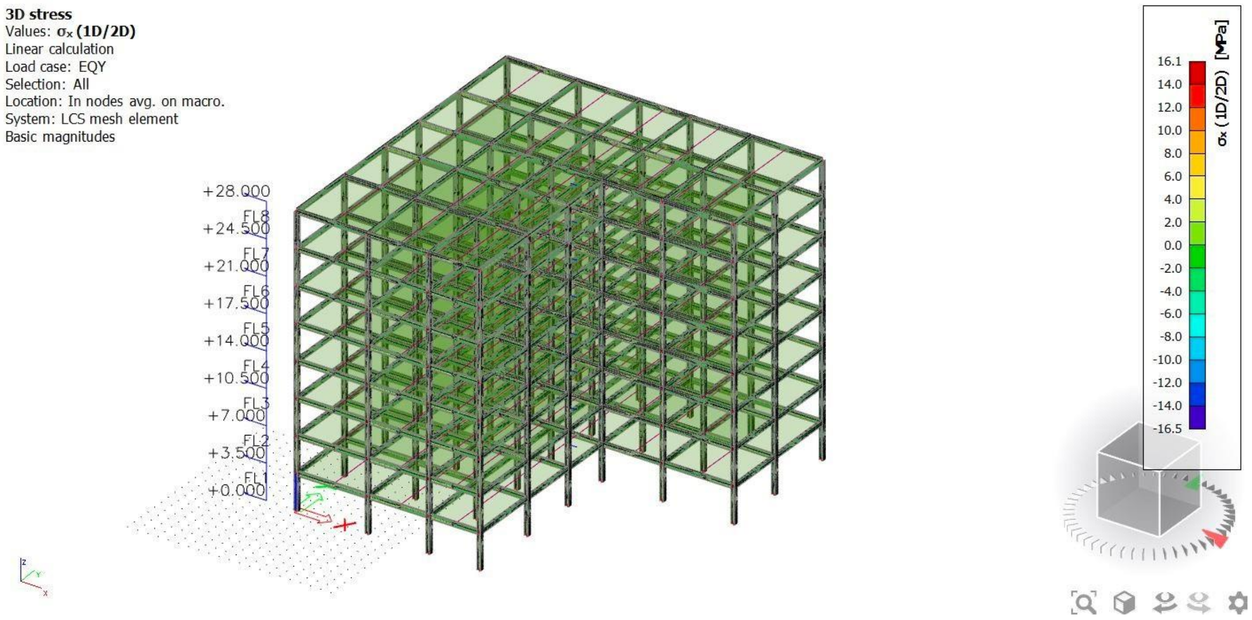
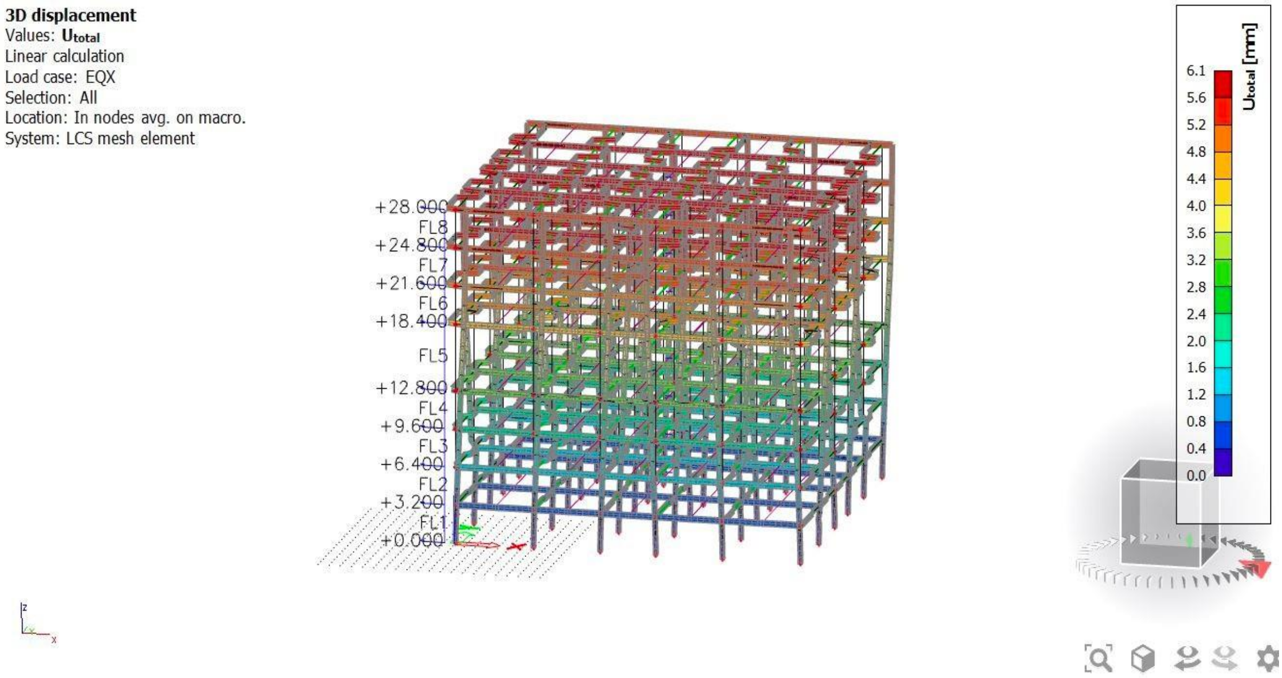


Figure 15. Stresses under EQY load case (plan irregularity).

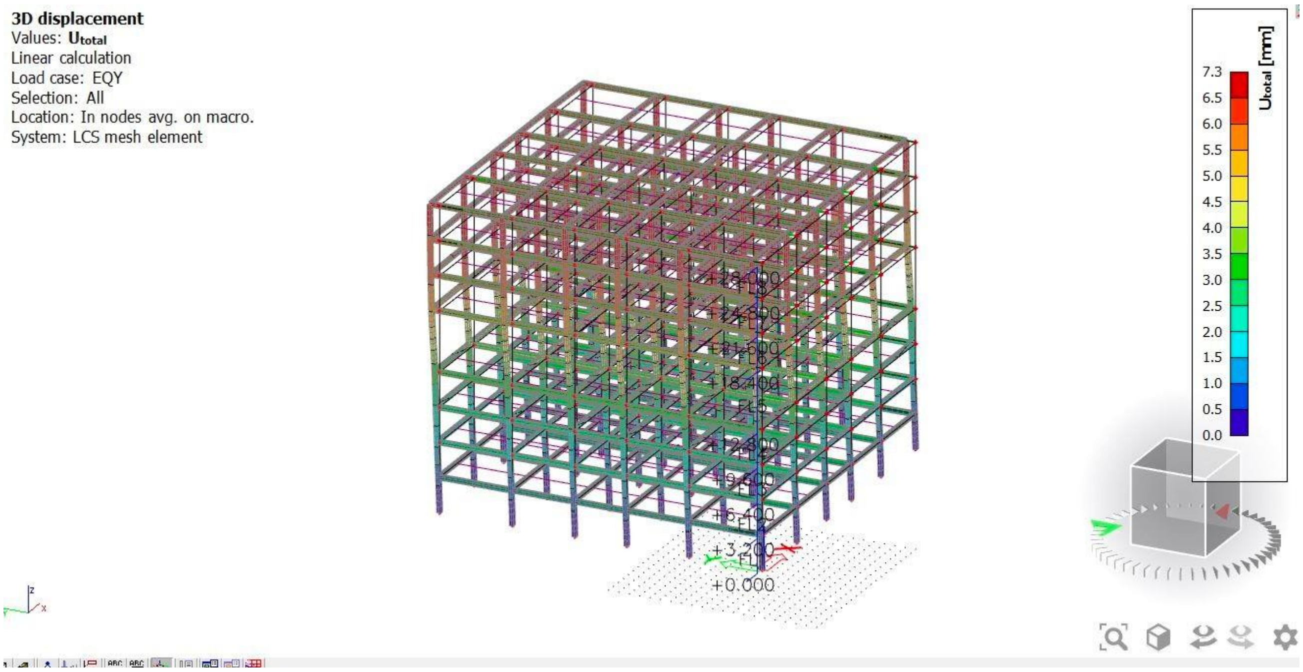
4.3. Structure with elevation irregularity

When the height of the 5th storey was increased to 5.6 m with the other storey heights being 3.2 m to keep the total structure height as 28 m, the seismic displacements in **Figure 16** were computed, for load case EQX. A similar diagram for case EQY is shown in **Figure 17**.



3D displacement
Values: U_{total}
Linear calculation
Load case: EQX
Selection: All
Location: In nodes avg. on macro.
System: LCS mesh element

Figure 16. Displacements for case EQX (elevation irregularity).



3D displacement
Values: U_{total}
Linear calculation
Load case: EQY
Selection: All
Location: In nodes avg. on macro.
System: LCS mesh element

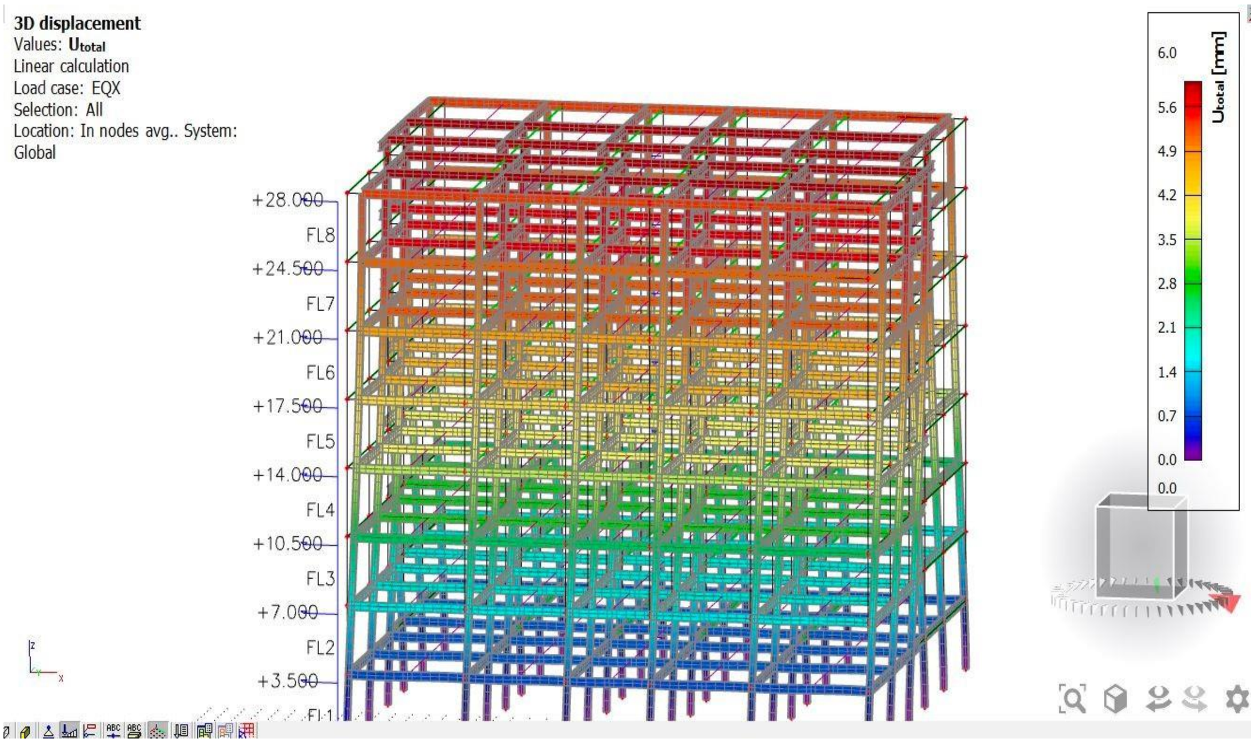
Figure 17. Displacements for case EQY (elevation irregularity).

As for the 3D stresses under the seismic loading, it was found that column grids C164 and C158 experienced the maximum stresses of −13.5 MPa and 13.5 MPa, whereas beam grid B188 had the maximum stress of 11.0 MPa.

4.4. Structure with mass irregularity

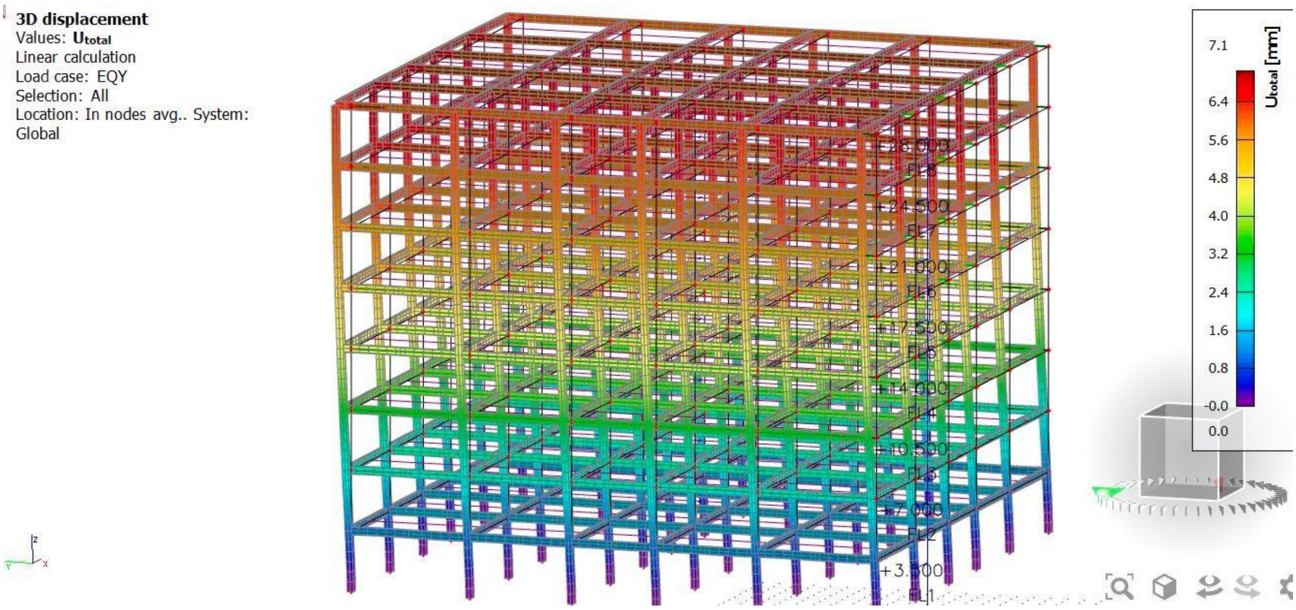
When the dead loads and live loads on the 5th storey were doubled, the calculated displacements for load case EQX and EQY are shown in **Figures 18** and **19** respectively. These show that the extreme displacements were 6.0 mm and 7.1 mm for

EQX and EQY respectively. The consequences of mass irregularity are noticeable; the beam and column at the top floor have become separated due to greater deformation and stresses.



3D displacement
Values: U_{total}
Linear calculation
Load case: EQX
Selection: All
Location: In nodes avg.. System: Global

Figure 18. Displacements under EQX (mass irregularity).



3D displacement
Values: U_{total}
Linear calculation
Load case: EQY
Selection: All
Location: In nodes avg.. System: Global

Figure 19. Displacements under EQY (mass irregularity).

As for the 3D stress results, it was found that column grids C20 and C14 experienced the greatest stresses of −14.4 MPa and 14.4 MPa while beam grid B68 had the highest stress of 11.4 MPa.

4.5. Structure with stiffness irregularity

With the introduction of X-bracings and different column sizes, the calculated displacements under EQX and EQY load cases are shown in **Figures 20** and **21** respectively. The extreme displacements were 6 mm for EQX in inner beams and 7.3 mm in inner beams and columns. These values occurred in the top two storeys.

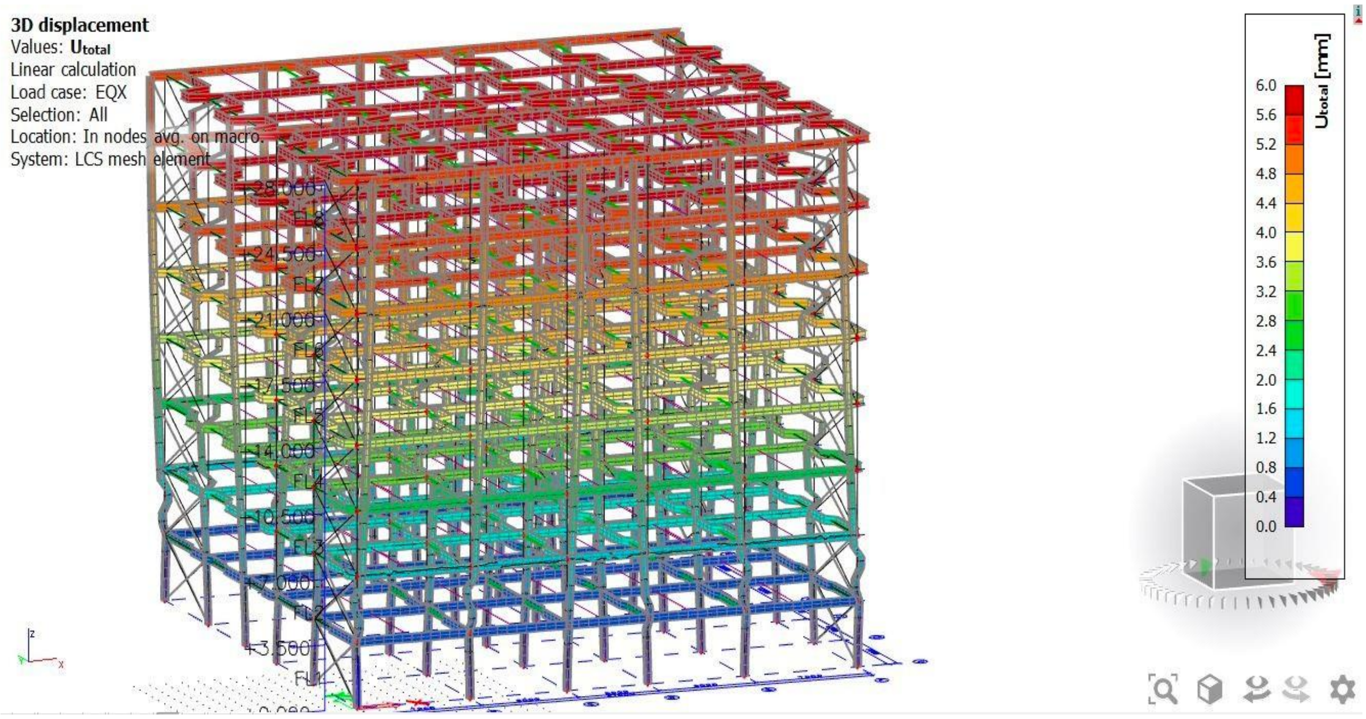

3D displacement
Values: U_{total}
Linear calculation
Load case: EQX
Selection: All
Location: In nodes avg. on macro.
System: LCS mesh element

Figure 20. Displacements under EQX load case (stiffness irregularity).

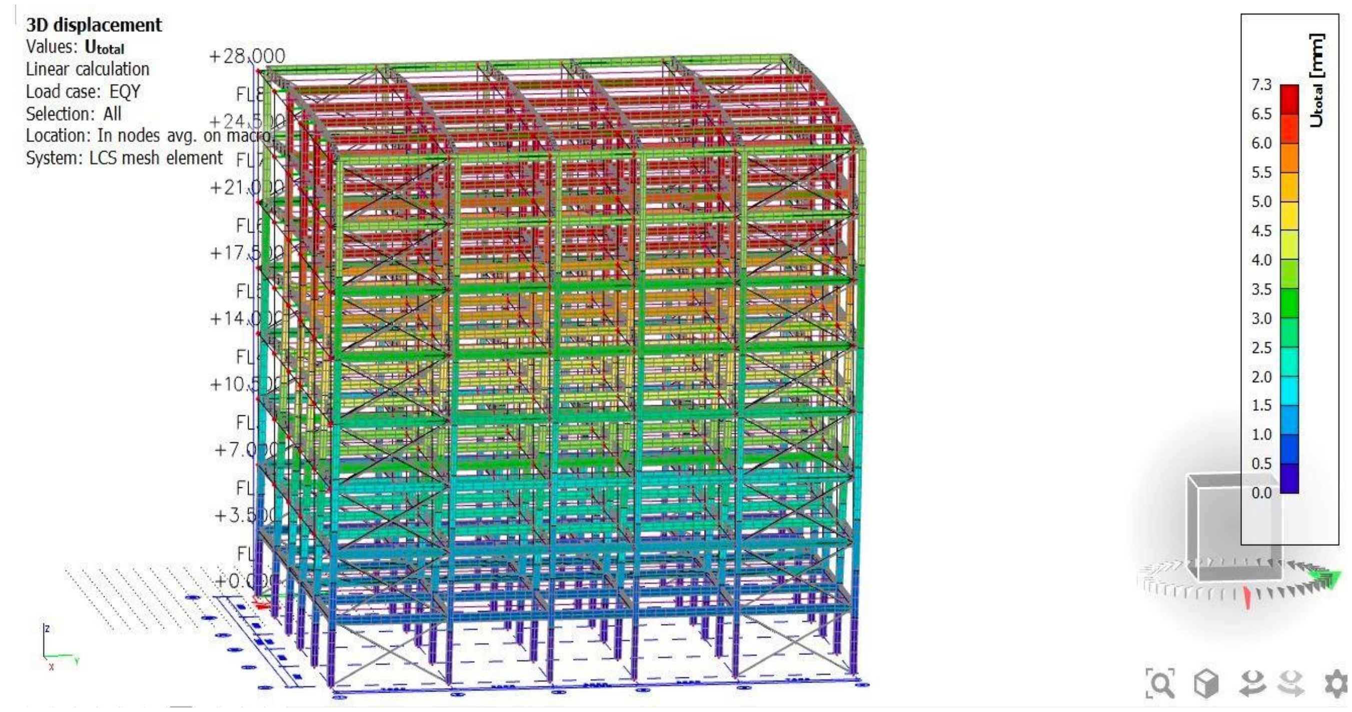

3D displacement
Values: U_{total}
Linear calculation
Load case: EQY
Selection: All
Location: In nodes avg. on macro.
System: LCS mesh element

Figure 21. Displacements under EQY load case (stiffness irregularity).

As for the 3D stresses, it was found that column grids X12 and X9 had the highest stresses of −15.7 MPa and 15.7 MPa while beam grids B68 had the highest stresses of −11.4 and 11.4 MPa respectively.

5. Discussion and conclusions

The dynamic response of hypothetical steel structures with and without structural irregularities has been successfully investigated, using SCIA [4] finite element software. Four kinds of irregularity were modelled, i.e., plan, elevation, mass, and stiffness irregularities, all of which were imposed on a hypothetical low to medium rise steel structure buildings of 7 storeys and 28 m height. In parallel with modelling of the variously irregular structures, a perfectly regular steel structure of the same height and number of storeys was also analysed with SCIA [4] software. Bay areas were kept the same in each case model, whether regular or irregular structure. Also, in each case the steel sections were UB 457/191/74 for beams, UC 356/368/177 and UC 305/305/118 for columns and L sections 50/50/5 for the X-bracings. The equivalent lateral force method was applied to the regular structure while the response spectrum method was implemented in finite element for the irregular structures. The dynamic responses of the structurally regular and irregular cases were simulated through calculation of 3 dimensional displacements and stresses in all parts of the model 7 storey structures. From the outputs of deformation and stresses, the following conclusions were drawn:

- All the structurally irregular models buckled more than the regular model and showed severer damage in columns and beams, under imposed seismic loading.
- under seismic loading, the regular structure had the lowest maximum deformations and stresses hence was significantly better in performance compared to all the irregular structures.
- Among the variously irregular structures, the model with stiffness irregularity performed the worst under seismic loading, as evident from the greater deformations and stresses.

The limitations of the present work are that it (a) assumes linear analysis for seismic loading, (b) does not include the effects of staircases and other secondary structures, which may be part of a real steel framed structure, (c) assumes the foundation behaviour, under seismic effects, is the same for all the structures modelled, both regular and irregular.

6. Novelty of the present work

The novelty of this research is that it analyses the dynamic response of a predefined structural model, for four types of structural irregularity simultaneously, based on the same control parameters and computational method. Also, even though the use of a building may change at some time, current literature on seismic vulnerability does not adequately address the impact of unexpected unevenness in mass distribution, but this research does. This work contributes to ability to optimize design of irregular structures to enhance seismic performance, mitigate risks of seismic damage and promote consistency in design and construction of earthquake resistant structures.

The findings from this and other research will contribute to updated information base, for cases where structural irregularities are unavoidable. The accruing body of information will eventually provide a basis for improving and reviewing best practice guides and codes of practice. Therefore, structural engineers will be able to design safer, more efficient, and resilient structures, in situations where dynamic actions such as earthquakes, winds and waves are significant factors in the design of structures. The methodology of analysis in this work is general and applicable to any kind of 3D framed structure. However, although this research considered four different irregularities, these may not cover the full range of irregularities in real structures for instance variations in vertical setbacks, floor thicknesses, etc. which could influence the structural response and vulnerability. Therefore, further research should consider a wider range of irregularities and different response spectra and structural model sizes, and a wider variety of practical structural configurations.

7. Limitations of the present work

As with all dynamic analysis methods, the results of calculations give useful insights into the response of a structure under seismic loading, especially with site-specific data and response spectrum analysis procedure. However, predicting the methods still cannot predict structural failure and deformations accurately even though potential failure modes may be identified. Limitations arise from the various assumptions in modelling and the input parameters used. Other limitations may be due to any simplifications made in the computational process to achieve resource efficiency, as built into programs such as the SCIA [4], ETABS [8], ABAQUS [12], and many others. Despite the limitations, the dynamics analysis of the type performed in the present work enables structural engineers to appreciate and accommodate the risks from structural irregularities when carrying out design for earthquake resistance.

8. Relationship to mitigation of or adaptation to climate change

A key element in mitigation of or adaptation to climate change is by using disaster-resilient strategies on steel structures. The United Nations General Assembly launched the International Early Warning Program to promote increased awareness around disaster management UNDRR [22]. For the development of this research, it is key to identify the following phases of disaster management regarding the effects of structural irregularities when it comes to seismic response:

- Prevention: Pre-disaster phase with special focus on preventative measures such as design standards for steel structures.
- Preparedness: Planning phase, this includes emergency management planning strategies to reinforce structural irregularities.
- Response: The immediate response after a seismic event, focusing on management of steel structures.
- Recovery: The short-term response restoring the main structural irregularities.
- Mitigation: The long-term response involving changes in local building codes and strengthening steel structures.

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data curation, JO; writing—original draft preparation, JO; writing—review and editing, JO and ZA; visualization, ZA; supervision, JO; project administration, JO; funding acquisition, JO. All authors have read and agreed to the published version of the manuscript.

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