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## Assessment of the stability conditions of an ancient stone masonry tower

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One of the major challenges in the scope of rehabilitation and repair of existing structures is the inspection and analysis of the stability conditions, which includes the detection of the damaged zones, cracking and defects, mechanical characterization of materials and further structural analysis of masonry structures. This diagnosis work is generally carried out not only based on experimental investigation on the laboratory but also by means of in situ nondestructive methods. Sophisticated nondestructive techniques have been developed and improved throughout the years and are applied to various types of structures in distinct fields, namely masonry structures. In this scope, the work presented here deals with a non-destructive approach to make a preliminary diagnosis of an ancient masonry tower, the Quintela Tower, in Vila Real, Portugal. The tower presents a square shape of about 5x5m<sup>2</sup> and has about 30m height and was built exclusively with granite. It presents some distributed cracking and a major concentrated crack near a corner in the north-west corner passing through the units and unit-mortar interface. The stone presents high degree of weathering in some places with detachment of small pieces of material. The inspection of the structure includes the application of GPR and boroscopy to characterize the cross section of the walls and stone slab at the base of the tower. Additionally, natural frequencies were obtained based on dynamic identification with ambient vibration. The characterization of materials (stone and wood) was carried out based on Schmidt hammer for the stone and on the pycnometer and resistograph for the wood. Additional characterization of the stone was performed based on SEM analysis aiming at understanding its weathering level. Besides the understanding of the structure and of materials of the masonry tower, the non-destructive approach enables also to derive the main basic properties for the numerical evaluation of the stability conditions of the masonry tower.

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### Introduction

The Quintela tower is a masonry structure located in the region of Vila Real, in Portugal. Its construction dates back to the XIII-XIV centuries (Fig. 1). The building is isolated, situated in a rural setting and surrounded by low-dwellings, and is located in the periphery of the Quintela settlement next to agriculture fields, near Ribeira da Marinheira, west of Vila Real.

This building constitutes one of the few examples of civil-militar architecture that proves an advancement of the typical low-medieval feudal land-ownership in the transmontan region. Quintela (the site), located in the civil parish of Vila Marin, had an estimated population of 16 inhabitants in 1530 and of 28 in 1721.

In terms of geology characteristics, the Vila Real municipality is integrated into a large structural unit (Maciço Hespérico) that represents the oldest structural unit of the Iberian Peninsula, where the most ancient rocks are located (granites, shale, quartzite and diverse metamorphic rocks).

The tower presents a square shape of about  $5 \times 5 \text{m}^2$  and has about 30m height settled on bedrock and was built exclusively with granite. It is covered by a four-sided roof having sloping ends and sides. The walls are crowned by pyramidal merlons with the rhythm marked by slits. The principal facade is perforated in the center by an entrance door on a level higher than the ground. The door and windows with semicircular arch evidence certain fidelity to the Romanic style, whereas the ogival relieving arch and the balconies with battlement parapets constitute an example of the gothic style. The lateral and posterior facades are symmetrical, with slit perforated and equally centered balconies. In the top of the facades, similar balconies exist in the corners with machicolations and parapets. In two of the facades, two gargoyles appear at the same height.

The connection to the superior floors from the ground floor is done by a timber stair located in the right of the entrance door. The second floor is accessed also through timber stairs with the same angle as the previous level and constitutes the "noble" part of the building. This description originally mentions the existence of an additional floor level that can be assumed to have existed previously as the supporting corbels exist, but are not used currently.

In the center of each one of the four walls are located doors that allow access to the balconies and have in the interior a segmental arch. The roof is supported by two wood trusses.



Figure 1. Various views from the Quintela tower: (a) northwest and northeast facades, (b) southwest and southeast facades, (c) views of the roof and border surrounded by battlement with merlons, (d) slit and balconies, (e) slit openings from the interior and (f) view of the trusses and roof.

The work presented here deals with a non-destructive approach to make a preliminary diagnosis of the tower, which includes visual inspection and the application of GPR and boroscopy to characterize the cross section of the walls and stone slab at the base of the tower. Additionally, natural frequencies were obtained based on dynamic identification with ambient vibration. The characterization of materials was carried out with the Schmidt hammer for stone and the resistograph for wood. Additional characterization of the stone was performed by SEM analysis aiming at understanding its weathering level.

### Material and structures

The materials found in the present state of the Quintela tower are granite used for walls, ground floor pavement and external access stairs. Cement mortar was used for repointing the stone joints in an intervention in 1982 and clay tiles were used for the roof. Some engravings on the stones used on the facades can be assumed as evidence of an ancient construction period.

Timber was used for the roof structure and the intermediate floor slabs. The floors of the first and second floor were built in 1983 with beams supported on existing corbels on the masonry walls. The type of timber used is French chestnut for the beams and flooring in Portuguese Pine.

The structural system is constituted by bearing walls of granite stone masonry and timber slabs for the floors. The bearing walls have a three-leaf configuration. The outer leaf measures, in average, 0.4m, the inner core measures 0.7m and the inner leaf measures 0.4cm, approximately. These values were obtained from GPR and boroscopy field tests. The inner core is constituted mainly of rubble, dirt and voids. These characteristic can affect the mechanical properties of the stone masonry walls in the tower. In particular, the weak collaboration among structural elements (walls, floors and roof) do not provide any effect in the connection of the overall structure, due to the fact that floors and roof timber structures are simply supported on the stone corbels sticking out of the masonry walls. In fact, neither timber nor roof existed for several centuries and only were rebuilt on 1982.

Three arches are used in the main entrance door and lintels for the window openings that are narrow (slits) towards the outside but widen towards the inside (where a column to support the lintel is observed), as illustrated in Figure 1e.

The boards of pine timber that compose the floor are nailed on transversal joists, which are supported by seven main timber beams. The main beams are simply supported on granite stone corbels. See Figure 2.



Figure 2. Constitution and distribution of beams and joists from the timber floors.

### Visual inspections

A preliminary visual inspection was carried out in order to locate and map visible damages in order to understand its distribution and to have a general idea about the reasons why the damages occurred. The damage maps were prepared with the help of the existing drawings that were obtained as blueprints, which dated back to 1983. Figure 3 illustrates the location and distribution of the damages and decay observed.



Figure 3. General view of the damages in the tower's facades: (a) southeast and (b) southwest facade and the (c) northwest facade and the (d) interior view of the northwestern wall.

Generally, the damages and decay were mainly cracking and weathered material (Fig. 4). Relatively to cracks, structural and nonstructural cracks were observed. The most important cracks concentrate in three different locations of the tower and are known to exist before the intervention in 1982. The most important structural damage is found on the northwest façade, which exhibits a vertically extending crack, which is thicker on the second floor level on the exterior façade. The crack has an estimated width of 2cm. Historical survey showed that the crack exists since the 1980s. This crack was repaired with a thick mortar during an anterior restoration intervention. Around those cracks are visible some thin cracks that started to appear after the first intervention. However, the main repaired crack did not showed to have reopened.

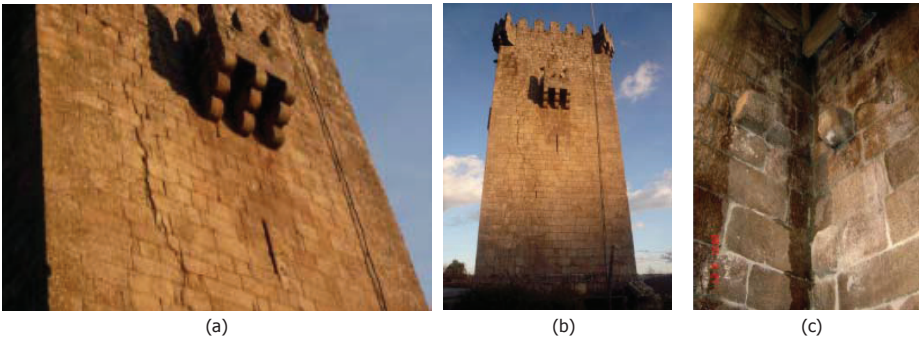


Figure 4. Detailed view of the damages in the tower: (a) main crack and (b) water infiltration.

Material decay was observed in timber elements (biological attack, water infiltration, moist spots) and in stone units (biological growth, stains due to humidity, water infiltration, vegetation). The decay in the timber beams placed under the timber slabs caused some deformations. In fact, water infiltration and biological attack are the main problems regarding decay on the timber elements. The stone units suffer from the erosion and spalling, mainly concentrated of the ground floor.

## Non-destructive tests

### Ground Penetrating Radar

The objective of this test was to use GPR to gain more information regarding the geometrical features of the cross-section of the walls. The inspections were carried out using a medium and high frequency antennae (800 and 1600MHz) and were performed in the ground, 1<sup>st</sup> and 3<sup>rd</sup> floors. Further information about GPR can be found in Binda et al. (1998) and Daniels (2004).

From the analysis of the acquired profiles, stones of irregular geometry were observed, as illustrated in Figure 5 but a three leaves masonry constitution was confirmed. The inner layer seemed to be the most irregular of the three leaves, composed approximately by stones with thicknesses varying between 0.26 and 0.40m. The outer leaf presents a more regular structure, with values close to 0.40m of thickness. Consequently, the infill dimensions ranged from 0.70 to 0.80m. Certain radargrams exhibited a certain decrease in the amplitude of the signal with depth. This loss of information can be attributed to the presence of humidity, which was well observed by visual inspection.

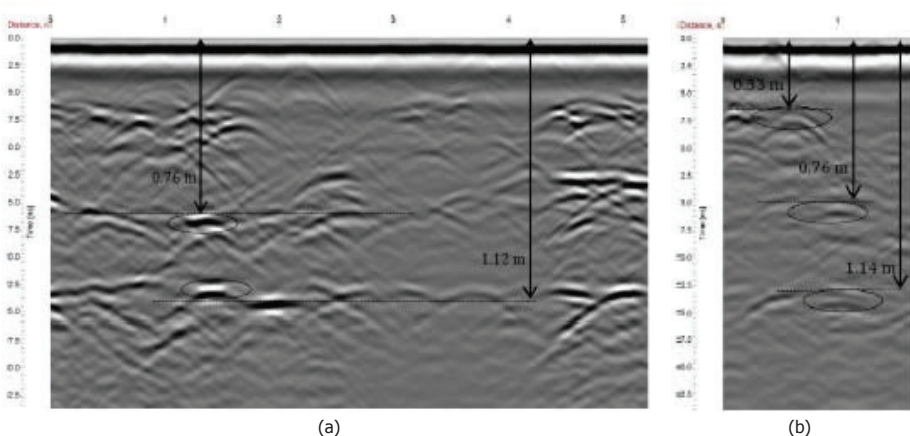


Figure 5. Radargrams carried out in the walls of the tower. Examples of an (a) horizontal and a (b) vertical profile are illustrated.

The slab of the tower is constituted by stones with relative similar longitudinal sections. As result of the GPR test (Fig. 6), the pavement slab thickness could be determined and also the thickness of the leveling slab for these stones. Regarding the supporting system, the obtained results were not much conclusive; however they may indicate the presence of a supporting structure.

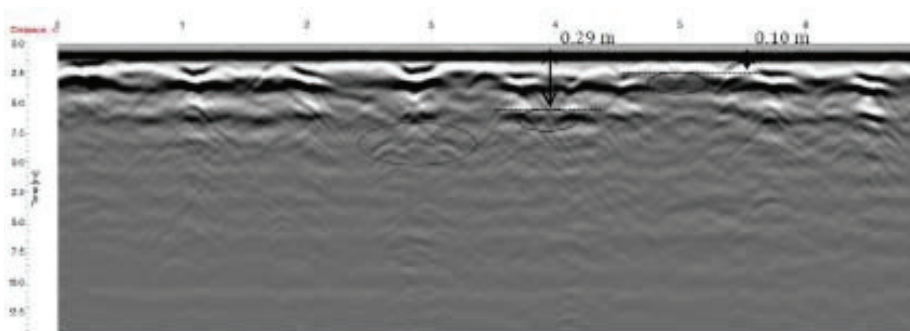


Figure 6. Radargram carried out in the ground slab of the tower.

### Resistograph

The resistograph measures the resistance to penetration of a small drill with 3mm of diameter (Rinn, 1994; Feio, 2006). This resistance is registered in each point of the drill path, and therefore, can be used to detect decayed areas and inner voids, as well as nodes. It is based on the micro drilling principle, which measures the energy required for maintaining same speed of drilling. This method is generally adopted to obtain density profiles of wood. Figure 7 illustrates the application of the resistograph in wood beams and the resultant graphic.

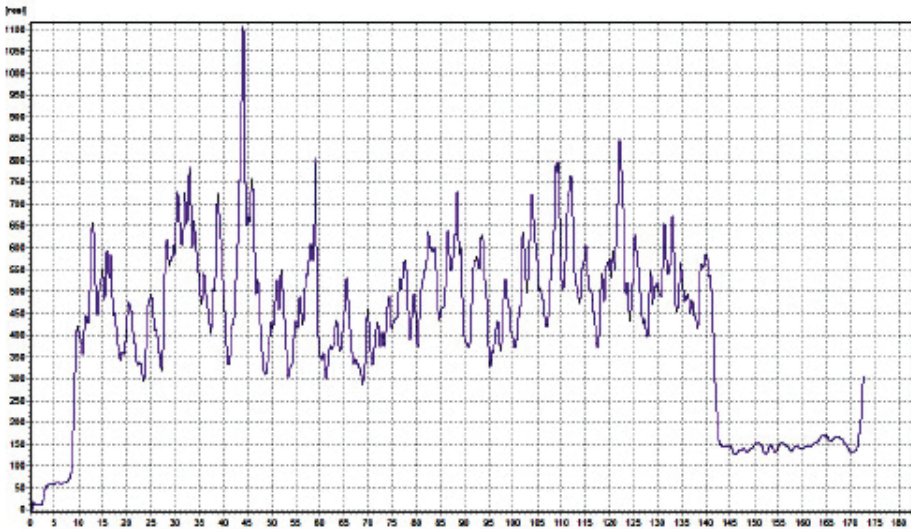


Figure 7. Application of the resistograph in wood beams and an example of the final result.

### Schmidt hammer test

The Schmidt hammer was applied in the interior walls of the tower in order to gather information on the surface hardness and, possibly, compressive strength. The surface hardness is only representative of a layer of 5cm depth. The measurements were carried out along two different heights: 0.75 and 1.5m from the ground of each floor. Some result variation is expected due to heavy infiltration on some parts of the wall. Four measurements were taken at each point and during analysis the average of these points were taken.

The results obtained show some consistency, which can be deduced that the level of deterioration on the surfaces of the walls is relatively uniform. However, when the values obtained are compared with the values for solid granite from literature, a significant decrease in the values is observed, which indicates loss of strength related to weathering. In some points, unexpectedly low values were obtained, which possibly indicates the occurrence of detachments from the stone surface.

### Measurements with boroscopic camera

The measurements carried out with the boroscopic camera allowed to observe the constitution of the inner leaf and, simultaneously, confirm the results from GPR. Therefore, three holes were drilled on the wall in

order to observe the thickness of the solid granite leaf as well as the depth of the inner layer, which was found to be approximately 0.4m, confirming the GPR results. This is illustrated in Figure 8.

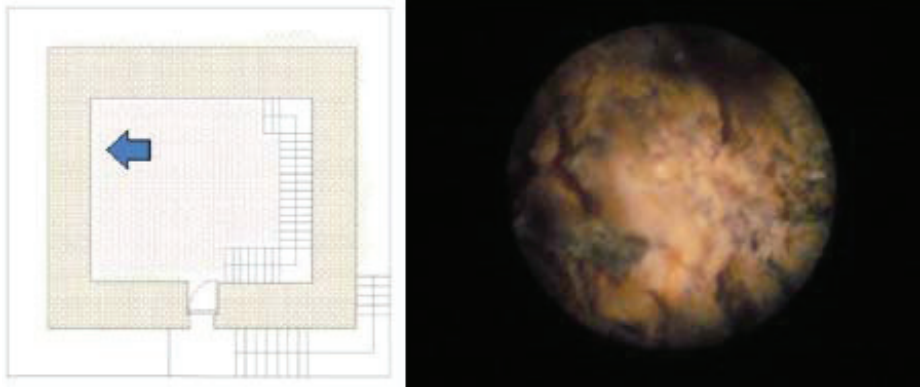


Figure 8. Inspection with boroscopic camera: location and image from the inner leaf.

### Other tests

Ultrasonic pulse velocity tests were carried out in situ and in laboratory. The average velocity found was 2500 m/s, which is characteristic of a stone with some degree of deterioration (Vasconcelos et al., 2007). Additional analysis of the surface of the stones by scanning electron microscope (SEM) showed evidences of weathering, as illustrated in Figure 9.

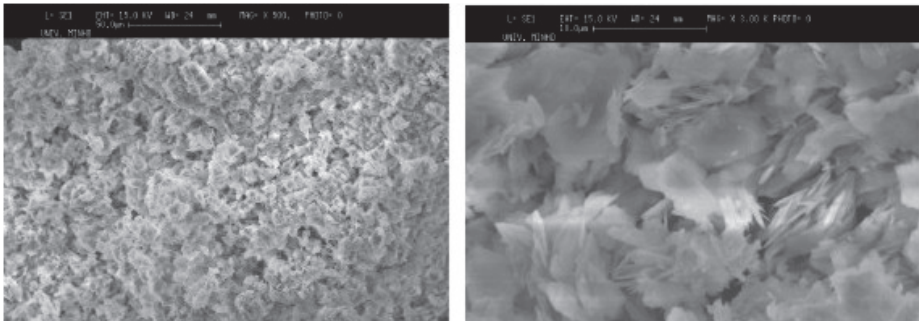


Figure 9. SEM images from the surface of the stone.

### Structural analysis

A finite element model was carried out to better understand the structural behavior of the structure under static and dynamic loads. The modeling of the three-leaf walls was simplified by assuming a homogeneous material along the thickness of the wall. Also since the weight of the timber roofs compared to the self-weight of the granite masonry is too low, the application of these loads was not considered in the analysis.

To calibrate the material properties of the model, a dynamic modal identification test was carried out in situ. A preliminary linear analytical model was done and the material properties were assumed taken into account the preliminary lab test on the granite and the fact that the wall was modeled as a continuum element (Fig. 10a).

The dynamic test was performed using the ambient vibration caused by the wind, which allowed the determination of the three principal mode shapes (Figure 10b) and Table 1. These mode shapes allowed to obtain the material properties for the numerical model, namely the elastic modulus of 1GPa. The other properties remained unchanged (Poisson's ration of 0.2 and density of 2000 kg/m<sup>3</sup>).

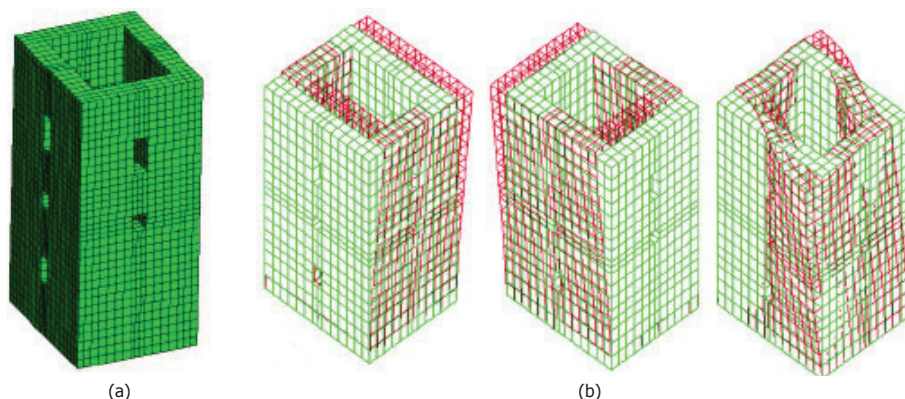


Figure 10. FEM model for the tower: (a) continuum model and (b) mode shapes from the modal identification analysis.

Table 1. Results of the mode shapes frequencies (initial model, experimental characterization and updated model).

	Frequencies (Hz)		
	Preliminary analytical model	Experimental Modal Identification results	Calibrated model
Mode 1	1.64	2.27	2.32
Mode 2	1.89	2.58	2.67
Mode 3	3.25	4.67	4.63

After calibrating the model, deflections and stresses were checked in an updated linear elastic analysis. As handcheck calculations anticipated, low compressive stresses were found in the results, where maximum compression stresses values of approximately 1MPa were obtained. Figure 11 shows the stress level in all the tower. It can be observed that maximum tensile stresses occur mainly around openings.

**Conclusions**

The Quintela tower has been showing signs of deterioration for several years, and although it has been subjected to several interventions, it still bears indication of damages, implying that those past interventions did not locate or solved the problem. Good practice indicates that a preliminary survey is fundamental to understand the structure. In this paper, a non-destructive approach to make a preliminary diagnosis of the ancient masonry tower was undertaken.

The visual inspection resulted in the verification that the main crack extending along the second floor does not seem to be active after the repointing intervention in 1982, although further tests and monitoring are necessary to confirm this assumption. The overlapping of the damage maps showed that the thin vertical cracks observed are following the same pattern of the main external crack. The possible reason of these vertical cracks could be due to soil settlement. Apart from this problem, no out-of plane or any kind of similar phenomena is observed by visual inspection, which implies that the tower does not seem to present severe structural problems.

The decay observed on timber slabs can be categorized as the decay due to biological attack, water infiltration and non-structural cracks in the contact point with the walls. The slabs don't seem to have any structural problems but the decay caused by water contact and biological growth can influence the structural capacity of the timber in the long term. The stone units suffer from diverse weathering process such as erosion, loss of material, detachment, loss of material, deformation-crust and biological colonization.

The dynamic modal identification test allowed the calibration of a numerical model, fundamental to understand the crack pattern and the occurrence of other damages.

Therefore, the tasks undertaken allowed to obtain information regarding the current conservation state of the structure and components, the geometry of the walls and calibration of a numerical model for posterior analysis.

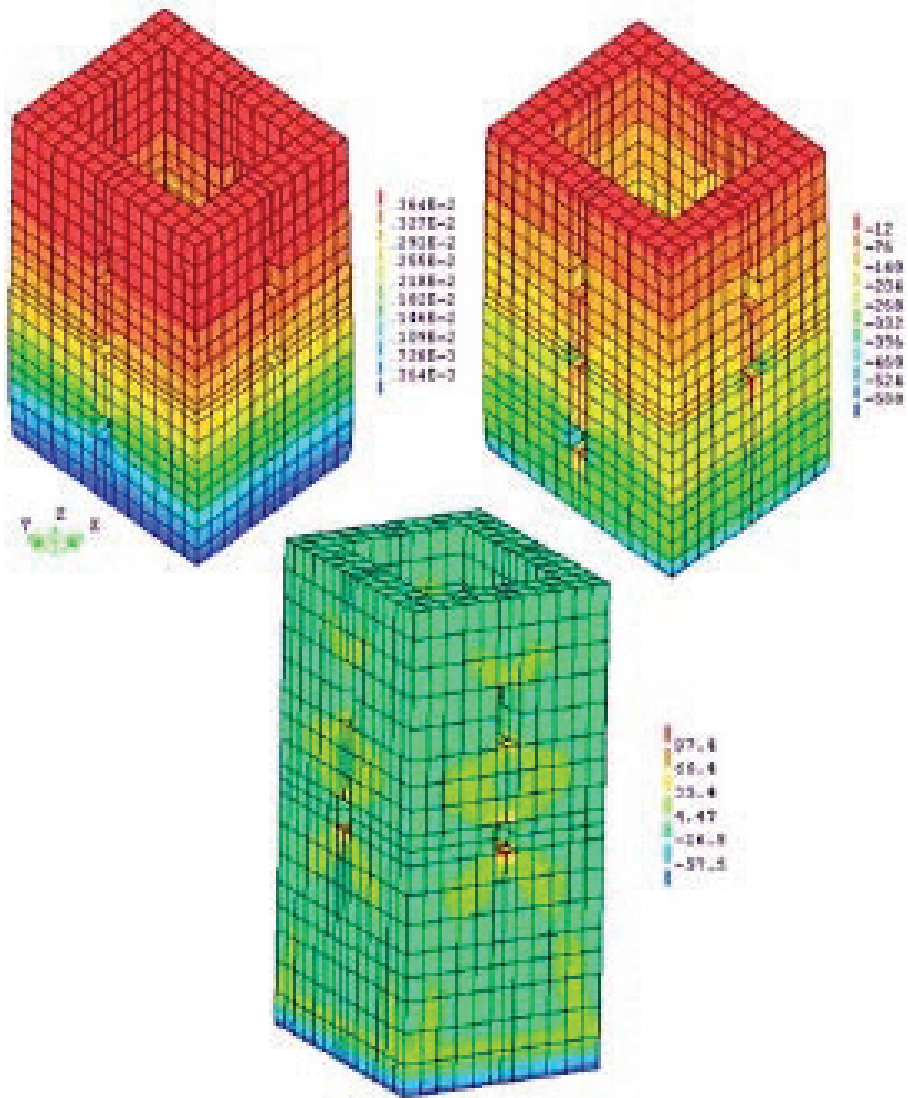


Figure 11. Updated FEM model for the tower showing stress levels.

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