12th International Conference on Structural Analysis of Historical Constructions
SAHC 2020
P. Roca, L. Pelà and C. Molins (Eds.)

THE COLUMN-LESS STAIR IN LORETTO CHAPEL IN SANTA FE, NEW MEXICO: STRENGTH ANALYSIS

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Keywords: Historical Structure, Finite Element Analysis, Spiral Staircase

Abstract. *A spiral staircase in Loretto Chapel in Santa Fe, New Mexico, has no center column to provide structural strength and stability. Some estimates say that the stair should have collapsed at first use. Yet, the stair has been used daily since its genesis in 1878. Explanations of the strength of the structure varied from "basic mechanics" to "miracle". This article presents a stress analysis of the stair using a finite element model. The loading is 16 persons on steps 1, 3, 5, …, 31 of the stair (as shown in an old photograph), the weight of the stair, and the weight of the railing. Stress computation was performed with a finite element model built and run in Abaqus CAE (Dassault Systemme, 2016). The analysis shows that the center spiral is severely stressed. The maximum Von Mises stress, which occurs near the top of the center spiral, is 1.7MPa. The ultimate strength of strong Engelmann spruce is 2.0MPa. The absence of the center column is significant because a center column would reduce the maximum stress in the stair to about 0.3MPa.*

1 INTRODUCTION

The Loretto Chapel in Santa Fe, the capital of New Mexico, has a spiral staircase with no center column to provide structural strength and stability. Some estimates say that the stair should have collapsed at first use (Bullock, 1978). Yet, the stair has been used daily since its genesis in 1878. Explanations of the source of the structural integrity ranges from simple 'physics' (e.g., Carter, 2010) to attribution to miracle. A landmark in the historic Old Town area of Santa Fe, the staircase has been the subject of many articles. A popular story about the genesis of the stair has been re-enacted in television shows and movies including "Unsolved Mysteries" and the 1998 television movie entitled "The Staircase" (Bobbin, 1998). The author of this present work did not find any numerical explanation of how the stair can support its own weight and the load that it carries. A good numerical explanation can be in the form of stress calculation using finite element analysis and comparison against material strengths. Many related examples of this kind of analysis for wooden structures include Invernizzi (2016).

This article provides finite element calculations to show: 1) The stresses in the staircase structure under heavy loading, 2) Which parts of the structure may be stressed most heavily, and 3) How a center column would reduce the stress.

Figure 1 shows the structure of the stair. The figure is an artist's rendering; but the only difference between the figure and photographs of the actual stair is that the figure eliminates the railing to provide clear view of the structure of the stair. The strength analysis in this paper will include the railing as a load, not part of the load-bearing structure. For the first two years of its use, the stair had no railing (Black, 2014). Making two turns of 360-degree spirals, the stair has a total of 32 steps, the 33rd 'step' being the balcony floor. (The number 33 is said to be the age of Jesus Christ when he was crucified.) Table 1 shows data used in the strength analysis. Specific weight is used to calculate the loading of the stair structure due to its own weight. The ultimate strength and the shear strength of the material (assumed here to be Engelmann spruce) are used not in the calculation but instead compared to the maximum stress in the stair structure.

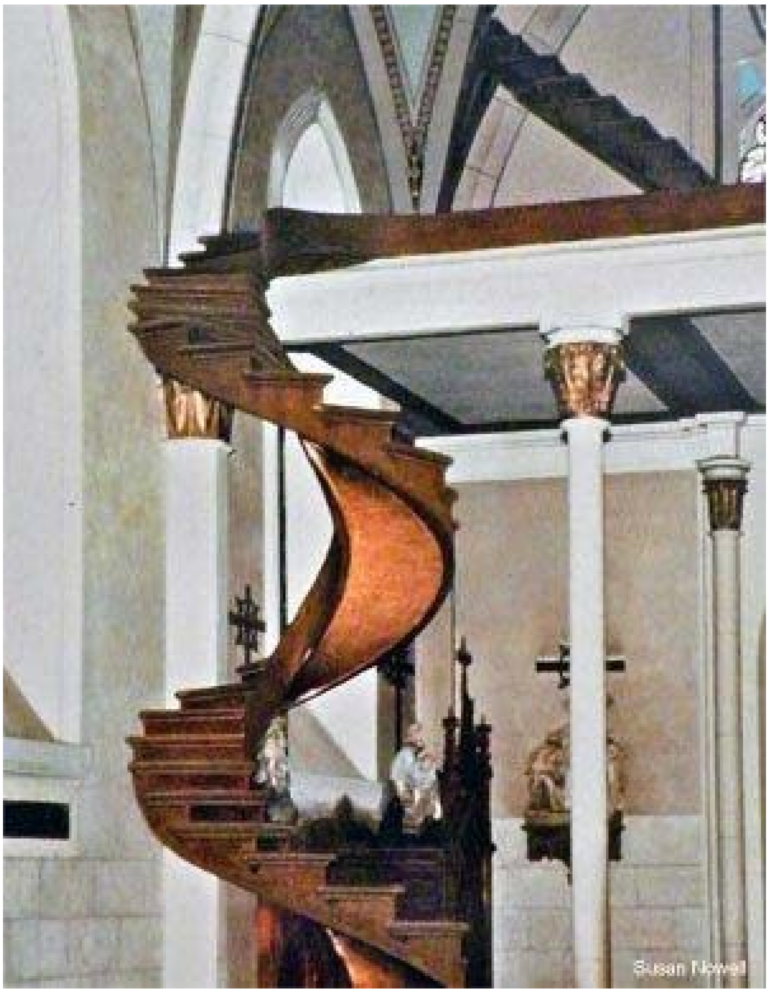

Figure 1: Staircase structure. (Black, 2014)

2 DATA

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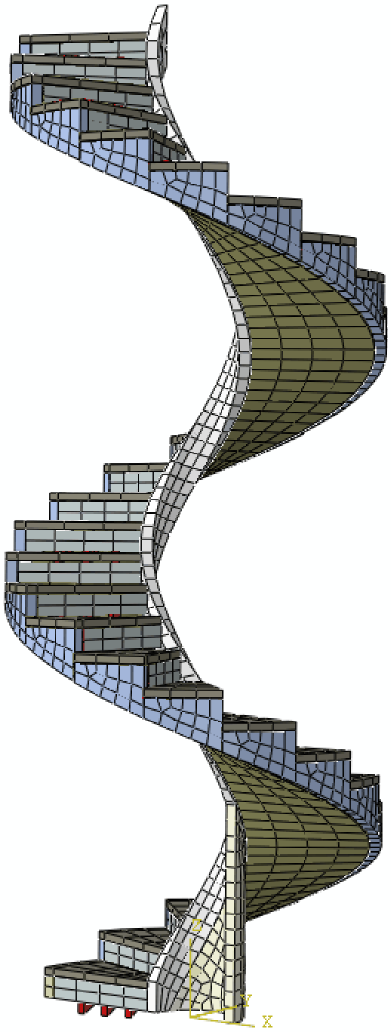
Table 1: Data used in strength analysis

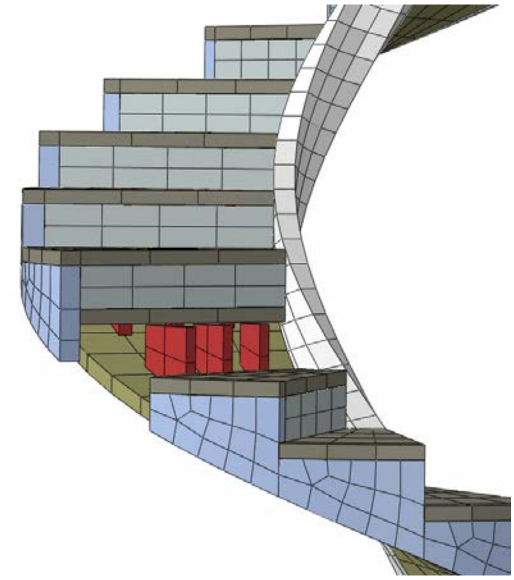
Parameter, unit	Value	Notes
Height, m	6.706	
Outside radius, m	1.224	Excludes railing structure
Inside radius, m	0.300	Excludes railing structure
Number of steps	32	The 33rd step is the balcony floor
Thickness of boards, mm	50.8	Assumed for all boards
Thickness of inner and outer helices, mm	76.2	
Weight of railing structure, N/m	200	Rough estimate. Small load.
Number of persons on stair	16	Heavy load based on Fig. 3
Weight of each person, N	800	Conservatively heavier than persons in Fig. 3

3 METHOD OF ANALYSIS

The results of the calculations presented in this article are in the forms of stress. In particular, Von Mises stress is a good overall measure to show the relative distribution of stresses throughout the stair structure. Compressive stress will be compared to the compressive strength of the material; and shear stress will be compared to the shear strength of the material. The stresses that the stair material has to endure is calculated below with a finite element model built and run in Abaqus CAE (Dassault Systeme, 2016). A mesh (Fig. 2) was created from the geometry of the stair, and used throughout this analysis. Figure 3 is a photograph illustrating a heavy loading scenario. Figure 4 is a model of the loads used in the stress analysis: Sixteen persons weighing 800N each stand on steps number 1, 3, 5, 7, …, 31. The weight of each person is assumed evenly distributed over the tread. The stair is also loaded by its own weight, plus the weight of the railings.



(a)



(b)

Figure 2: a) Mesh of the stair, b) Cut-outs showing internal braces.

Figure 3: Photograph used to estimate loads.

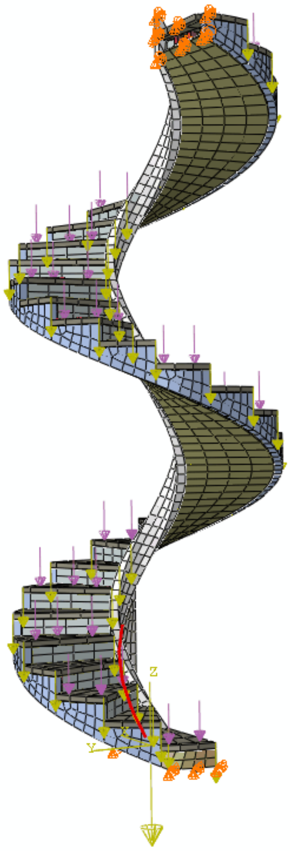
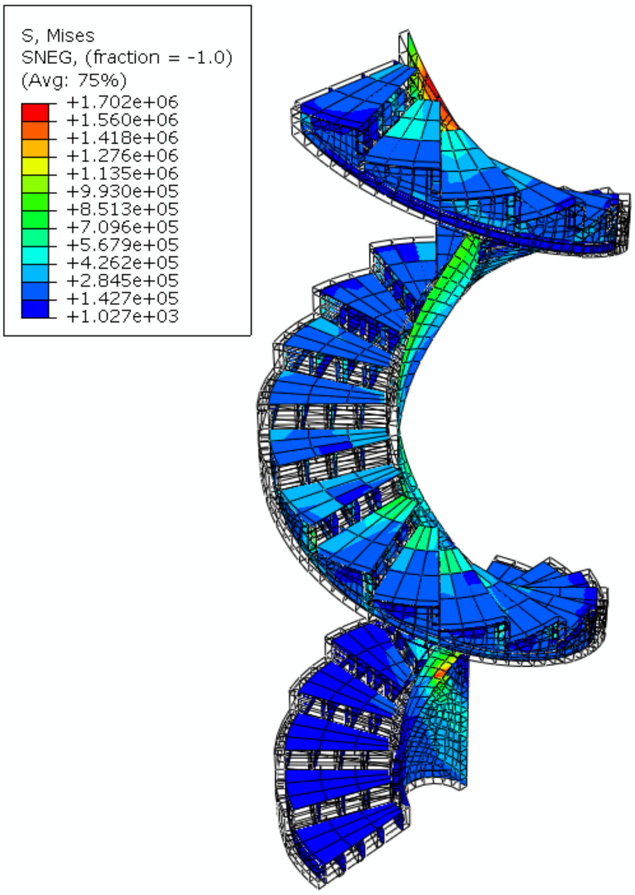
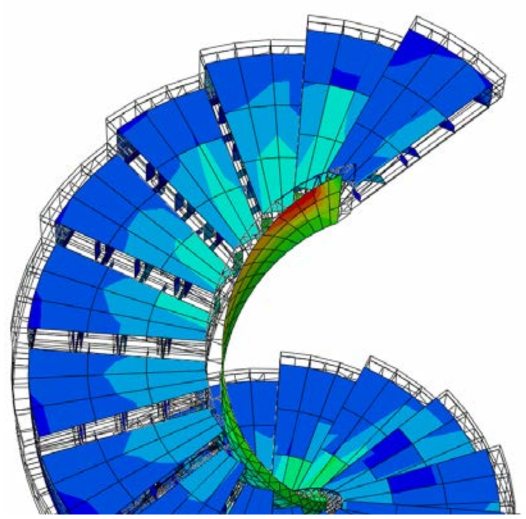


Figure 4: Boundary conditions: Fixed on the top and bottom of the stair. Loading: one person each on steps 1, 3, 5, …, 31; gravity (weight of stair), and weight of railings.

4 STRESS CAUSED BY THE LOADING

Figure 5 shows that the center helix is heavily stressed. At the location with the highest stress, near the top of the inner helix, the Von Mises stress is about 1.7 MPa. The strength of wood is very anisotropic: fracture depends on the alignment between the stress components and the direction of the wood grains. High compression (negative normal stress) in the direction of the wood grains can cause separation of grains (Fig. 6a). Shearing stress parallel to the direction of the grains (see Fig. 6b) also can cause separation of grains. Because anisotropy is important in wood, the compressive and shear stresses are calculated and shown in Fig. 7. The greatest compressive stress is 1.4 MPa. The location of the greatest compressive stress is again in the center helix. The greatest shear stress is 0.75 MPa. The location of the greatest compressive stress is also in the center helix.

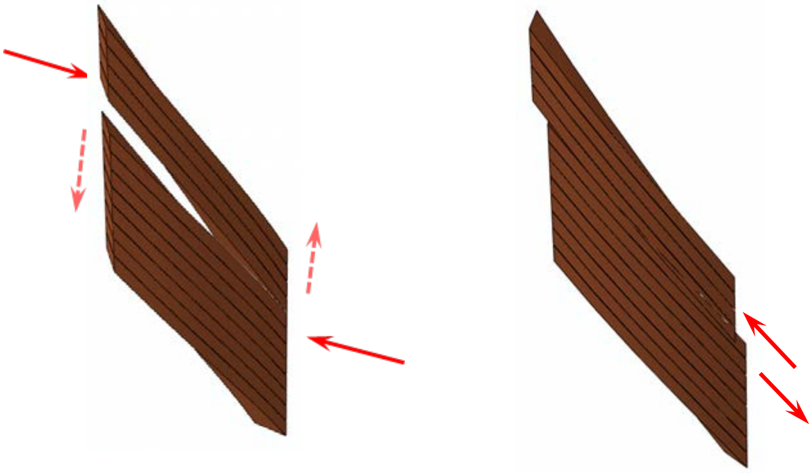




b)

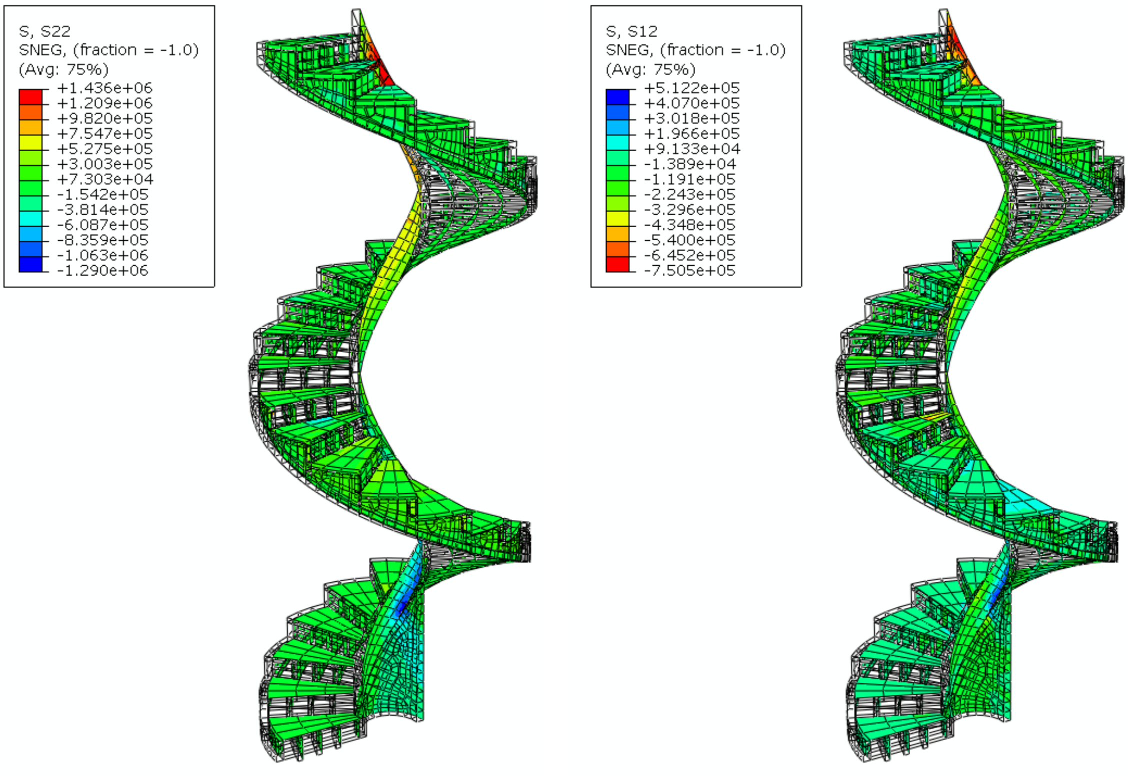
a)

Figure 5: Von Mises stress a) Side View; b) View from above



a) b)

Figure 6: Wood fracture caused by a) Compressive stress; b) Shear stress



a) b)

Figure 7: Damaging stress a) Compression; b) Shear

The material of the stair must be strong enough to withstand the above stresses. Knight (1997) investigated the material and concluded that it was a sub-species of spruce. If the material is Engelmann spruce (which is stronger than most other spruces), it would break at its ultimate strength of 2.0MPa if compressed in the direction of the grains (which is the most damaging stress loading. Wood is much stronger in other loading directions.) If more weights load the stair (for example, a heavy person on each step), it is quite possible that the weights of the persons and the weight of the stair together will break the stair structure. The most likely location of the fracture is the center helix. It is also possible that the stair material is an even stronger Sitka spruce whose ultimate strength is 4.0MPa (Green, 2001). However, the cold location where Sitka spruce grows is many hundreds of miles away from Santa Fe, and it would have been difficult in the 1870's to transport the wood to Santa Fe. On the other hand, Engelmann spruce grows in New Mexico (Green, 2001).

The high stresses from the analysis confirm the assessment that it is difficult for the stair to bear the load (about 14kN from 16 persons plus the railings) plus the stair's own weight (6014N). Thus, the concern that the stair might have collapsed upon loading was justified. A spiral stair without a center column was not only rare but also difficult to design. A center column would serve well as a backbone to the stair. Though downplayed by some experts (e.g. Carter, 2010), the absence of a center column may well be significant.

5 THE IMPORTANCE OF A CENTER COLUMN

Figure 5 shows that the center helix, especially the top part of it, is by far the most heavily stressed part of the stair. Suppose, then, that the center helix were replaced by a more complete hollow column that supports the stair from the ground, as illustrated in Fig. 8. Then, this support would reduce the stresses around the center of the stair. The stress reduction would give a numerical value to the importance of a center column. Below, the above analysis process is applied to the hypothetical design in Fig. 8. The boundary conditions and loads are the same as those shown in Fig. 4.

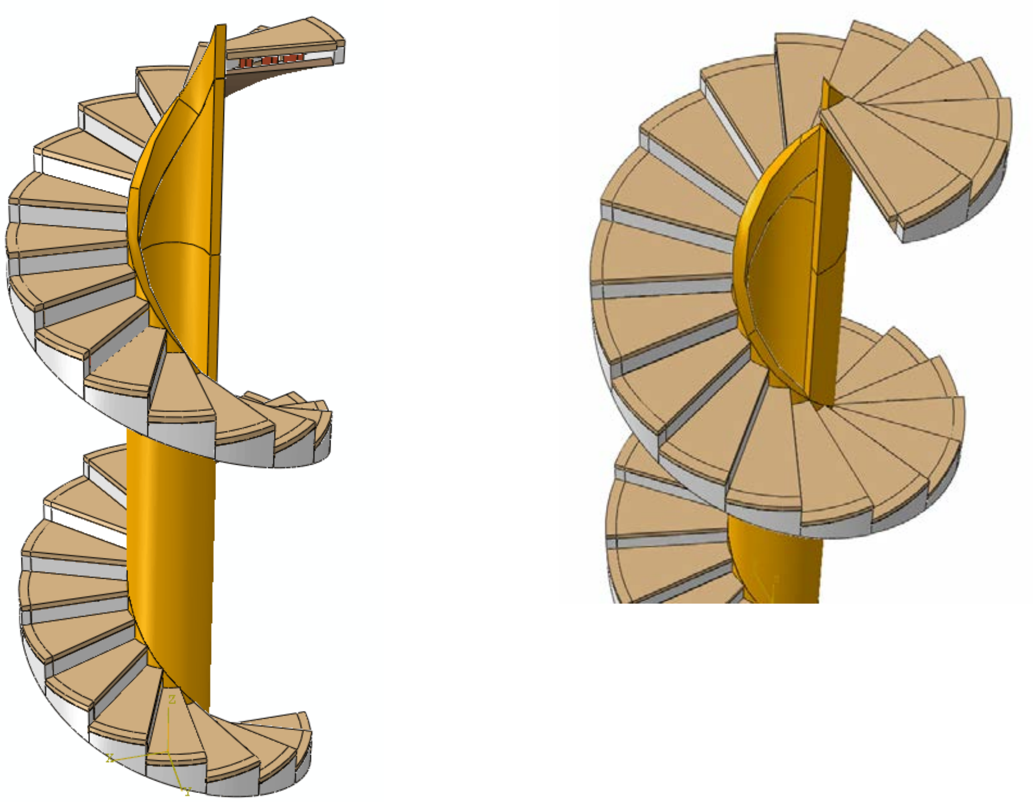


Figure 8: A hypothetical design, the same as the original design but with a center column.

Figure 9 shows that, with a center column, the highest stress in the stair is now around 0.3MPa. The location of the highest stress is on the outside wall at the top of the stair, near the place where the balcony supports the stair. The highest Von Mises stress, which occurs around the center of the stair, is just around 0.28 MPa. Those stresses are about eight times lower than the stress around the center helix of the stair without center column. Thus, the stair without a center column is about eight times weaker than an equivalent stair with a center column. This analysis shows that a center column is very important to the strength of the spiral stair.

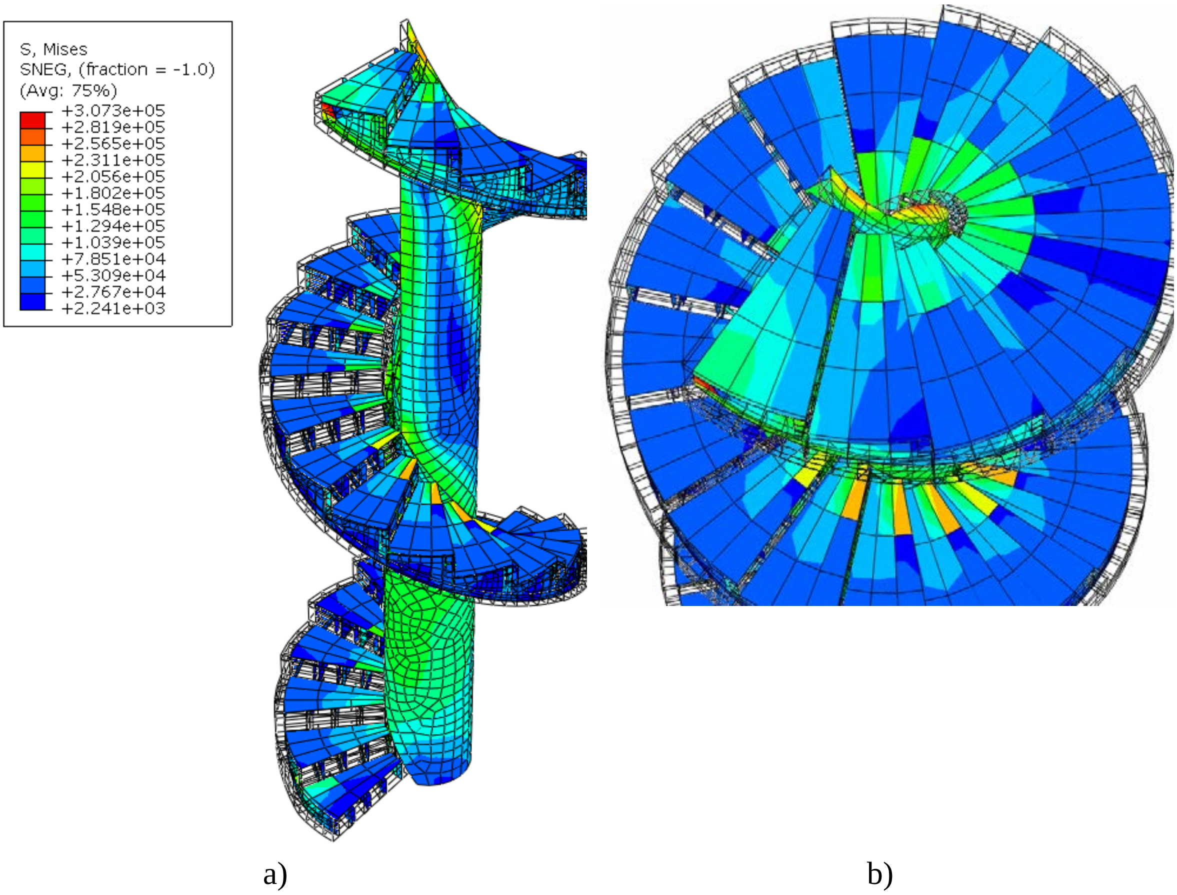


Figure 9: Von Mises stress in a stair with center column: a) Side view; b) A view from above.

6 CONCLUSION

When loaded with one person every other step, the column-less stair is heavily stressed. The center helix sustains the heaviest stress, especially at the top where the stair is attached to the balcony. The highest stress is about 1.7MPa. Thus, the center helix material must be a strong wood like Engelmann spruce which can sustain stresses up to about 2.0MPa, or a stronger wood. If more weights load the stair (for example, a heavy person on each step), it is quite possible that those weights and the weight of the stair together will break the stair structure. The absence of a center supporting column is quite significant. When loaded with the same load as the column-less stair, a similar stair design with a center column would be stressed to just about 0.3MPa maximum.

Although spiral staircases are common in architectural heritage buildings, few lack both a center column and a stair well that supports the stair from the ground. Most spiral staircases have a center column. The Bramante Staircase at Vatican's St. Peter museum lacks a center column but has a stair well. So does the triple helical staircase of the convent of San Domingos in the Bonaval district of Santiago de Compostela. Angelillo (2016) published an elegant proof of the stability of that staircase – evidence that a stair well that supports the stair from the ground would significantly strengthen a spiral stair.

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