Reverse Engineering Mesh based Deformed Simulated Part into Computer-Aided Design (CAD) File Format

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1. Introduction

The proposed challenge involved the reconstruction of the given 3D model VRML mesh (.wrl) file into an identifiable 3D model and recovering its obfuscated design information. The given VRML file represented a 3D model which was a Computer-Aided Design (CAD) 3D solid model and included its design information (eg: Stress, Material, Features) and had a static simulation study run: for when an adult steps on to it. This reconstruction was required to result in a CAD file with recovered design features and specifications so as to be able to stack these bricks on top of each other, and identifying the maximum stress experienced by the brick.

2. Analysis of given information

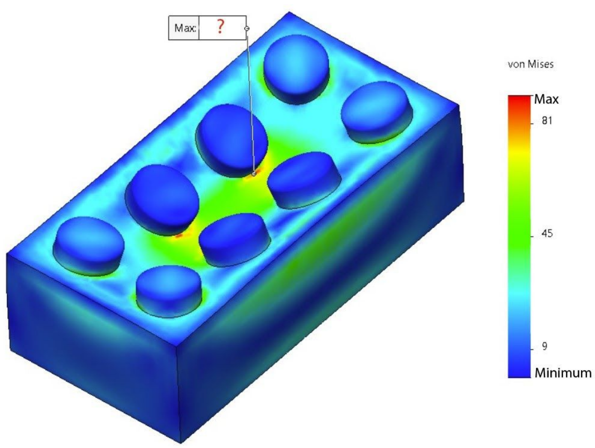


Fig 1: Given Scale range without units of the mesh File

The challenge provided us with a VRML mesh (.wrl) file to identify and replicate the file into a 3D model CAD file of the brick. In order to view the file we used CAD software to gather information, and found that the model was a deformed mesh of the static simulated part, with the color map displaying the scale of stress being applied. We were also provided a scale with reference [legend] to the color map on the mesh, which helped identify the type of stress that was being applied. It was also told that the file had missing features on the interior of the brick. Two Alpha-numeric codes were found embossed onto the mesh file, on the interior of the model L1 38564 & 2-252. Scaling the stress seen in the color map stress scale [Fig.1] it was found that the max value is 90 units. The unit was however yet to be determined.

3. Reverse Engineering the Model

To begin with the reconstruction, we proceeded to gather the dimensions. Implementation of both: a Product development oriented mindset and a Reverse engineering mindset, helped identify solutions to the problems faced during the study. The material chosen for the brick was ABS, as similarly sized bodies are found to be using ABS as well. And as the challenge mentions the brick is similar to a LEGO brick, this was a justified choice.

A. Elemental Lengths Summation

The dimensions were gathered from the base and height from the vertex edges, where least deformation was seen. We did so by summing up the elemental lengths of the mesh (edge of triangles) along the length of the dimension. Sizing the studs on the file was a slight hassle, only because the stress had caused the circular face to be expanded into an oval-ish shape, which meant measuring the radius of curvature of the deformed faces on the corner of the brick wouldn't be accurate. So, choosing the studs in the middle, as they were deformed only on one axis of the ellipse [or so apparent], meant that their minor axis would help us to find the radius of the circular face with slight error. Because the circular boundary of the studs were filleted, the mesh formation along the boundary was not consistent so elemental length summation did not work for this feature. The stud radius was verified, by constructing reference geometrical planes along the studs close to the center of the brick. On these planes, mean value is obtained from the 4 studs close to the center, and were found precise w.r.t. the Elliptical method. The height of studs was determined using elemental summation of lengths of mesh. The placement of the studs was determined similarly, and was validated while working on the stacking mechanism.

B. Stacking Mechanism

Once the dimensions were identified, we had to rebuild the missing interior features of the brick, which were dependent on the stacking mechanism of the brick. Walls of the brick were found in contact with the studs when placed on top of the other. Two ways of doing so were devised:

- By adding grooves on to the interior of the walls, which then made contact with the studs.
- By adding tubular extrusions underneath the brick.
- And, one where both of these were implemented.

The features were calculated using the formula below:

$$L= 2*A+3*B$$

$$W=2*A+B$$

$$2*A=B$$

L: Length of the brick

W: Width of the brick

A: distance between wall to stud's center

B: distance between 2 studs center.

These features were tested with some variations in the model like ribs across tubes and between walls, whichever would help us identify with similar stress deformation would be our best approximation.
The identification of the stacking mechanism was dependent on the simulation results.

C. Extraction of VRML mesh file

To figure out how the model was produced in the first place, and to have a clearer idea of the constraints needed to reverse engineer it. We were able to extract our own VRML mesh file from a rough simulation study on the CAD software and found the following:

- The VRML mesh produced may/may-not have true scale deformation.
- The exported mesh file of the given simulation, contains all parts as a simplified mesh which are color mapped to scale on the legend.

4. Simulation Study

We proceeded to run static simulations on all the variations of the model described above with the following constraints:

- Weight of an adult stepping onto the brick is our approximate force applied.
- The deformation seen in the mesh file is not of true-scale and maybe exaggerated.
- The numbers on the scale [given in Fig.1] are the only exact values provided, to validate our model and study.
- The selection of units on the CAD software is seen to be evenly spread on different softwares and are provided with the options to see the values in [PSI, KSI, bar, MPa, Pa]. Further reducing the number of cases.
- However, the characteristic deformation seen on studs and the above surface is of importance to us, as it describes and helps verify the behavior of the model under stress.

These constraints were the method of validation to verify whether the model tested was an equivalent part to the given file in the challenge or not.

A. Determination of constraint values

So as to perform the simulation,following data was acquired. We learnt that the force put in by an average person while walking is about 1.25 times the person's weight[1]. Putting that together with the average weight of an adult (which is about 180lb[2]), the force exerted by the person comes up to be 225lb. A range of values inclusive of this were used to identify the model from the set of proposed models. And, because the force was that of an adult stepping onto the brick, the applied force was put onto the studs of the brick.
The true scale deformation of the brick required a force which was much greater than the average human weight and hence it was concluded that the deformation was an adjusted/exaggerated view of the original.

The values on the legend of the Von mises stress, was our target[Fig.1]. After iterating over the different cases with different models, it was found that the stress values were close to the provided scale when used with Megapascal [MPa] force units.

To produce a similar legend-

- KSI required a force greater than 6000N
- Pa required a force lesser than 300N
- Bar required a force lesser than 300N
- PSI required a force lesser than 300N

Since these scales required a weight of either <30kg or >600kg, hence these scales were neglected.

The right model wasn't yet identified. We decided to compare the behavior of the studs and top surface under stress, as while iterating between the different models we had hypothesized, we noticed the variations in deformation behavior that helped us eliminate one of our proposed models. The model with ribs connecting the middle tube to the wall of the brick was neglected because it generated a completely different topology on the top surface of the brick as compared to our target.

B. Determination of model features using study data.

After running simulations on the above data we found a finite number of cases to implement within our proposed model:

- Brick model, which consists of tubular extrusion underneath, testing with varying thickness and height of the tubular extrusion.
- Brick model, which utilizes grooves on the internal walls.

These simulations with considerations from the VRML mesh file produced, showed that the part(s) were meshed together into one single file. This led us to believe that because the mesh there was a consideration that the internal structure that may have been in contact with the ground in a practical scenario, may have been ignored [for simplification] and only the outer boundary of the brick was used as a fixed geometry.

This information and comparison of the behaviour of stress on the surface and the studs of the different models, led us to believe that the brick model with tubular extrusion without grooves on the internal walls was the closest model in terms of all the above gathered knowledge.
The case with grooves (on internal walls) was neglected as the behaviour of the surface was evidently different [the maximum stress area was greater] from the given mesh file. [Appendix-B]

5. Conclusion

Our approach to the study and keeping the product development process in mind helped us make the choices and identification of the constraints for the simulation. We learnt that file information can be recovered from an unlikely source given the data is analysed with a proper methodology and good constraints. When done so, the process becomes an efficient tool for such a 'reverse engineering attack'. The surface behavior under stress deformation helped us isolate features which were missing from the model, which mimic the function but may not have the same appearance. Iterative and empirical studies helped us reach further consensus on the feature sets to validate the model.
These feature sets may not be accurate but when put under stress behave similarly to the model given to us. This error can be justified by tolerancing adjustments which are made with mechanisms functional considerations. Even with all of the above steps, we were unable to identify the significance of the given codes in the model (L1 38564 & 2-252).

The maximum stress that the brick can bear is 90.19 MPa

6. Acknowledgement

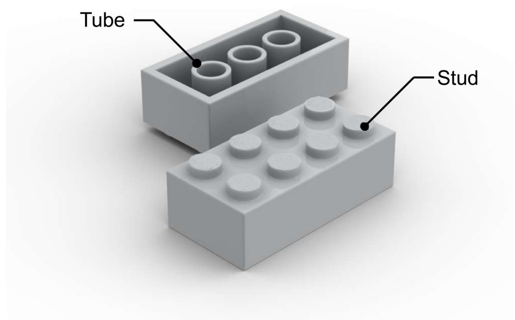
Dr. Rajesh Kumar for encouraging us with his vision for engineering students and helping us with resources and providing a comfortable environment to work in.

7. References

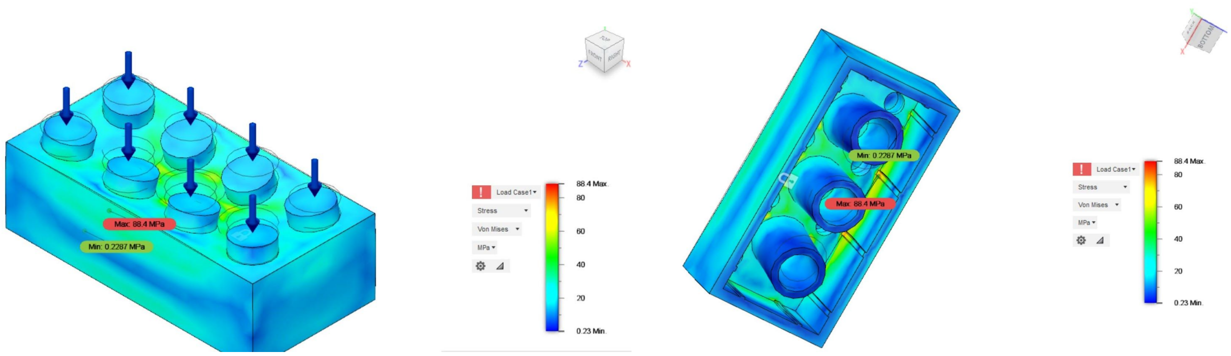
[1] **Ground reaction forces at different speeds of human walking and running, J Nilsson, A Thorstensson, 1989.**
https://pubmed.ncbi.nlm.nih.gov/2782094/#:~:text=The%20peak%20amplitude%20of%20the,2.0%20to%202.9%20b.w.%20respectively.&text=The%20vertical%20peak%20force%20increased,impulses%20and%20peak%20forces%20decreased.

[2] **Average weight of an adult.**
https://www.reference.com/science/average-weight-human-being-1186bf58b9307867

8. Appendix



A. Figure showing Studs and Tubes on the Brick



B. Figure showing the model with groves