Analysis and design of structural members of a pipe winding machine using finite element analysis

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Abstract

A structure used to wind large coils of plastic tubing was experiencing problems with large deflection. The final project assigned to students sought to analyze the cause of the problem, then to look for a solution to redesign the structure. Since cost is also important, the students have to design a low cost machine structure. Therefore, some optimization was expected to be carried out. One-dimensional beam and frame models were used and the solution by direct stiffness method is carried out by MatLab and some results validated by I-DEAS and NX CAE tools. Finally, preliminary calculations were done by mechanics approach. From an observation of the results, a design change of the size of the structural elements is attempted. The learning experiences of assigning this real life application as a final project to the senior undergraduate students taking the elective finite element analysis course is discussed.

Introduction

Corrugated plastic tubes are installed in the gardens at home or at commercial sites. These are used to drain or to irrigate the water or attached to the gutters to drain the roof

Figure 1: Commercial corrugated plastic tubing [1]

water away from the house or a building (Figure 1). There are different winding machines available in the market to manufacture and to wind the tubing in to large coils for

Figure 2: Commercial plastic tube coiling machine [2]

packaging and subsequently to transport to the dealer sites. Figure 2 shows pictures of some of the machines posted on the internet [2]. Depending on the type, size and capacity of these machines, the price ranges from $5,000 to over $100,000 per machine. A careful observation of the machine in Figure 2 reveals that the support condition of the spool is similar to a simply supported beam. Another possibility can be cantilever support. Although the simply supported condition can take more load to support the fully coiled pipe weight plus the tangential pull force, the cantilever support offers an advantage perhaps at the cost of excessive deflection of the spool rod and hence the full coil. The advantage is due to ease of assembly and removal of the coil from the machine without having to remove one of the supports of the otherwise simply supported spool assembly. Some companies manufacture low cost cantilever supported machine structures on order. However, they need to be carefully designed.

Keeping the above views, the purpose of this paper is to discuss the analysis and design of a simple pipe winder machine which has the problem of excessive deflections at one end of the spool supporting bar. Two student groups were assigned this problem as a part of their final project in applied finite element analysis taught by the author. The final learning experiences of doing this project included an understanding of modeling a complex machine structure for analysis by the structural mechanics where possible and by the finite element analysis. Many of the statics course concepts (free body diagrams, equilibrium in in 2-D and internal loads), and solid mechanics principles (deflection and stress of statically determinate and indeterminate problems) have been realized by the students during the course of carrying out this project. Use of modern CAE tools to validate some of the results and to optimize the structure proved to be very challenging for the students. Figure 3 shows the hand-drawn schematic of the machine structure that the author discussed and given to the students. It shows the main setup of the model along with the possible loads and few critical dimensions.

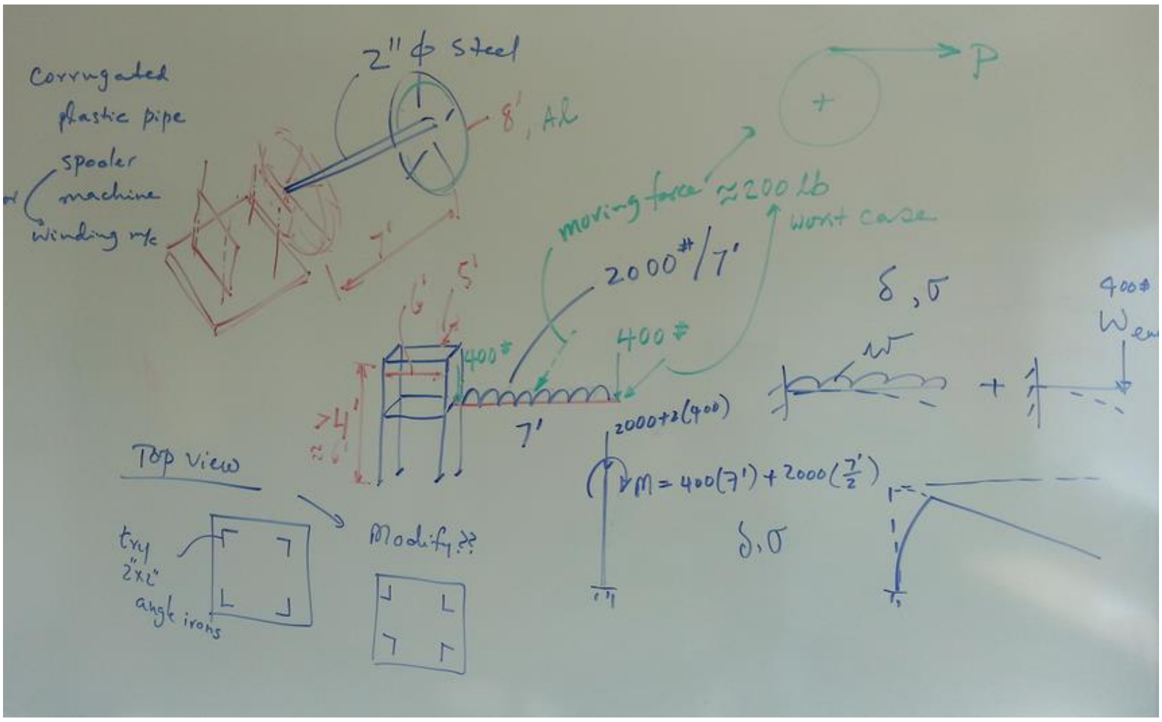

Figure 3: Hand-drawn schematic of the machine structure with critical dimensions and the statically equivalent models

In Figure 3, the loads caused by the weight of the two end wheels of the spool, and also a distributed load over the cantilever which represents the weight of the cantilever and the coiled pipe are shown. Both loads act in the vertical. There is another load in the horizontal which represents the pull-force from the part of the pipe which is about to be coiled. For the preliminary calculations this pull-force is neglected because it is much less than the other two and it would have brought another dimension to the problem. If the structure will stand the high vertical loads it should also stand the smaller horizontal load. One the groups used English units while another group used SI units while doing the project. The assumed data is as follows with approximate SI units within the parenthesis:

Data

Spool rod diameter = 2 inches (50-mm)

Length of the 2-inch spool rod = 7 feet (=2.134 m)

Diameter of the full spool = 6 to 8 feet (=1.829 m to 2.4384 m)

Height of the machine = more than 6 feet (> 1.83 m)

Weight of the steel spool rod + the end wheels = 400 lbs (=1780 N)

Weight of the plastic spool = 2000 lbs (=8900 N approx.)

Total weight acting on the spool rod = 2400 lbs (=10676 N)

The span of left support structure (frame) is made up of angle irons = 6 feet approx. (1.83 m)

Angle iron size = 2-inch x 2-inch (=50-mm x 50-mm)

Assumptions

Students used the following assumptions:

- for solving for the maximum deflection of the end of the cantilever the whole problem is divided into three partial problems: beam - torsion bar - frame
- horizontal loads are neglected
- the frame should be built by standard L-profiles 50x50 mm (t=2.5 mm)
- for the cantilever and the torsion bar which builds the connection between frame and cantilever a hollow steel (C60) bar with diameter D=100 mm and d=92 mm is chosen
- material properties are assumed to be linear

Figure 4 below shows the model of the hand-drawn sketch given to the students. The shows the loading due to weight of the spool and the pull force on the spool bar.

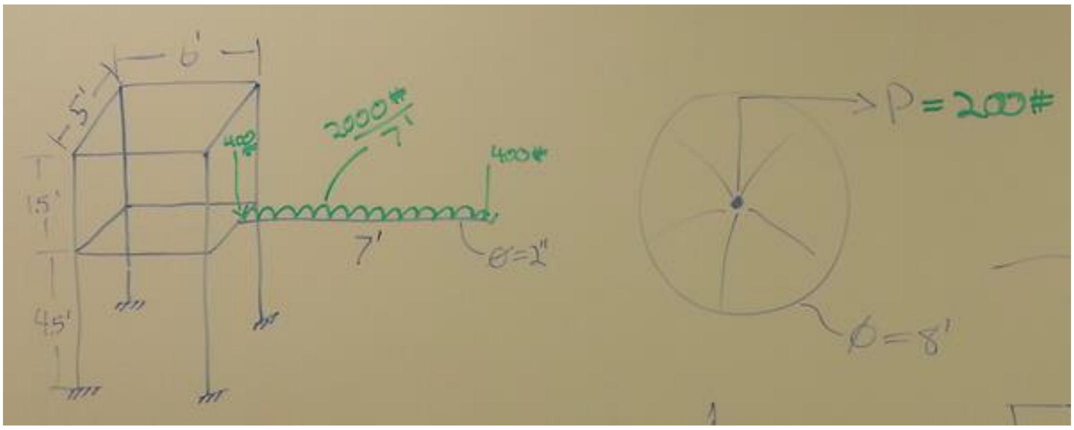

Figure 4: Simplified model of the spool coiler machine structure

Finite element models

As already mentioned, the problem has been divided in to three parts to be able to calculate the simplified models with 1D elements in MatLab.

Beam

All the load of the system is transferred to the cantilever beam. Beam elements are used because it mainly will bend in the vertical direction. To get a dimension for the bar the maximum deflection of this element is set to be limited to 50 mm. So the minimum diameter of the rod should be at least 75 mm. That is 1.5 times the diameter of one of the former groups chose. In order to save weight and to increse the rigidity of the bar, hollow section has been chosen. One of the other groups used solid round bar for their analysis. Based on the hand claculations for the maximum stress, C60 steel material has been chosen. Detais of these calculations will be provided later in the next draft of the manuscript.

Torsion Bar

The beam is connected to a bar which is placed horizontally between two members of the frame part. The load which is introduced to this element is the reaction force at the bearing of the beam. For practical reasons I used the same type of bar as for the beam element.

This element does not change the forces but it has a noticeable contribution to the deflection at the end of the cantilever. The connecting bar will also bend in vertical direction but my assumption is that this has way less influence on the deflection than the torsion. Allowing this element to bend would introduce forces to the frame which have a horizontal direction. So the problem becomes a grid problem and by that much more complicated but probably not much more accurate.

Frame

The structure which stands on the ground at the left and carries the cantilever is assumed to be a frame. This structure is three-dimensional but as the introduced moments from the torsion bar only act around the z-axis the structure is flattened to a two-dimensional frame. The symmetric parts are represented by doubling their area moment of inertia and their area. Detailed calculations will be provided in the next draft of the manuscript.

MatLab code has been developed for the beam and the frame models following the direct stiffness method documented in standard finite element textbooks such as Logan [3]. Based on the simplified model planar beam and frame model in MatLab, a total deflection at the end of the cantilever of around 25 cm (=10-inches) has been obtained, which is slightly higher than what may be acceptable in the real machine. However, this satisfies the limit set on the maximum deflection at the beginning of this paper. Some details of the solution are as follows:

- end deflection of the spool beam = 47.2 mm
- rotation of the connecting bar at the left support with respect to the length of the cantilever = 37.7 mm
- rotation of the frame with respect to the length of the cantilever = 164.1 mm
- buckling of the frame = 0.2 mm

This solution is certainly not correct because of the crude assumptions and simplifications made. Also, superposition principle has been used to sum the deflections. But the amount of deflection will have an influence on how the loads are applied. For example, the calculations are made assuming that the beam is parallel to the horizontal but in reality it will have a negative angle to it caused by the rotation of the frame and the torsion bar. This all will change the results.

To validate some of these results, CAE tool by NX I-DEAS and UG-NX have been used by the students. Figure 5 shows the FE model using I-DEAS. The frame on the left consisted

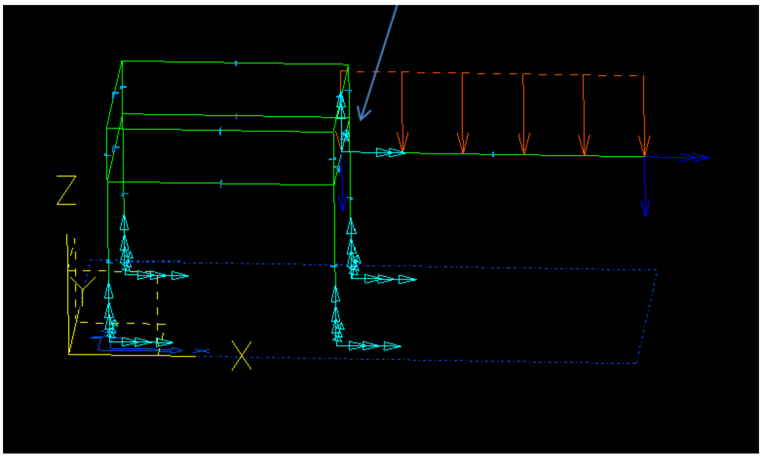

Figure 5: FEA model using I-DEAS CAE tool

of many members. The maximum end deflection obtained by this model was nearly 12-

inch (30-mm) which is higher than the model used in the MatLab computation. For the MatLab model the effect of deflection of the frame members is not properly accounted for due to laborious setting time involved. The maximum von-Mises stress predicted by I-DEAS is around 198 ksi (1365 MPa). The yield strength of the material used in the analysis (of C60) is around 490 MPa, thus predicting failure of the members by yielding. Therefore, the design has to be iterated to either change the geometry (larger size sections) and/or stronger material, which directly influences the cost of the machine.

To get better results a total 3D analysis has been attempted using UG NX of the entire system. However, no significant change in results was noticed, thus confirming to the students' learning outcome that 1D analysis may be sufficient and required to be performed before a full-blown 3D model is developed.

Learning outcomes and Conclusions

The students realized that the simplified 1D model gives an idea of what the deflection could be and what has the biggest contribution to it. They noticed that the stiffness of the frame is a big problem. One way to improve that would be to shorten the horizontal connections. But this is probably not possible because it needs that size to put a prime mover (such as an electric motor) to drive the machine (spool). So another way would be to use more horizontal connections or to use stiffer members.

By playing around with some input data such as what has been used in this project, the students realized that based on the modeling assumptions and the hand calculations simplified model can be powerful in understanding the concepts of the finite element analysis course and just not rely on a CAE tool to give nice results. They learned to question "how" and "why" about everything that they have control on. Redesign and its implications are better understood through this project. As one student comments: "In the end I would say if the pipe winder is well engineered it would be possible to build a very cheap version of it by using simple standard profiles. However other problems will come up like the design of the bearings and connections of the profiles."

References:

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