Final Report for Practical Work of the Course ENGG1300 of Group C9

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Abstract
This report aims to summarise the practical work done for the course ENGG1300 – Fundamental Mechanics in the second semester of the academic year 2024/25 by Group C9. This report introduces the problem presented to the group in the practical work, the process of drafting and verifying, and the methodology of the solution, the theorems and principles on which the solution is based, the results and quantitative analysis of the results, and the conclusion and reflection on the practical work.

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Contents

Introduction

The group was presented a problem to design and realise a structure using only ordinary newspapers and transparent plastic adhesive tapes. The problem further specified that the said structure shall observe the following conditions:

1. The structure must stand on its own without any external support.
2. The height of the structure must be between 780 mm and 800 mm.
3. The structure must not weight more than 1 kg.
4. The structure shall be able to bear at least 500 N of load without excessive deformation when being compressed by two wooden plates of 480 mm × 480 mm × 10 mm.

1. Theorems and Principles

In preparation for the practical work, and in the process of performing analysis, the group consulted various materials for building their knowledge and establishing a basic understanding of the principles and theorems that may be useful for the practical work.

The theorems and principles that were used in the practical work are listed in this section. For avoiding repetitive contents, only those theorems and principles that are beyond the scope of the course ENGG1300 are listed.

1.1 Buckling and Euler's Load

It was introduced that under compressive load, sudden large deformation may occur in the member, which is termed as **buckling**. To quantitaively describe the boundary load at which buckling occurs, **Euler's Load** is introduced [1]. It is given by:

$$P_{cr} = \pi^2 \frac{EI}{L^2} \tag{1}$$

where P_{cr} is the Euler's critical load, E is the Young's modulus of the material, I is the moment of inertia of the cross-section, and L is the length of the member.

The greater the critical load, the more stable the member is. By inspection, it is trivial to see that to obtain a greater critical load, it is desirable to have a greater moment of inertia I and a smaller length L.

1.2 Radius of Gyration

The radius of gyration k is derived from the moment of inertia I of a cross-section [2]. It is given by:

$$k = \sqrt{\frac{I}{A}} \tag{2}$$

where A is the cross-sectional area of the member.

Assuming the crosee-sectional area A is constant, by the conclusion of the previous theorem, a more stable member will have a greater moment of inertia I, and thus a greater radius of gyration k. It is therefore concluded that a member with greater radius of gyration k is more stable.

2. Designing and Drafting

In the designing and drafting phase, the group has established a basic model, which is composed of three components: the major members, the supporting members, and the restraining piece. These three components have different functions and are carefully designed to have different shapes and methods of production. Figure 1 shows an overview of the model.

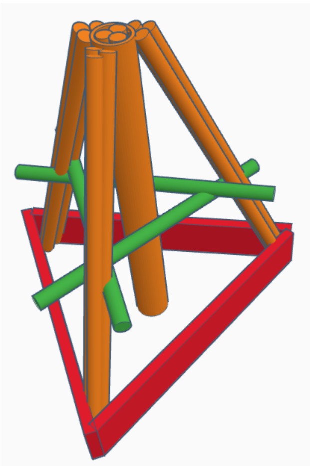


Figure 1. Overview of the model. The major members are shown in orange, the supporting members are shown in green, and the restraining piece is shown in red.

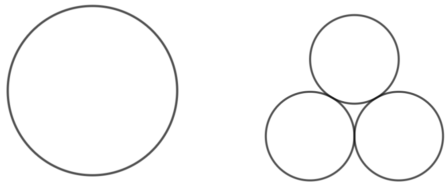
2.1 Major Members

The major members are one straight column erected vertically from the ground, and three slanted columns connecting the ground and the top of the vertical column. The points where the slanted columns contact the ground are the vertices of an equilateral triangle whose circumcenter is the point where the vertical column contacts the ground.

The major members are the longest members of the model and bear the most load. Therefore, they become unstable as the length increases as shown in Equation 1.

2.1.1 Pipe Configuration

To address this issue, the major members were fabricated by combining three densly rolled newspaper pipes (termed as the **tri-pipe configuration**, Figure 2b) as opposed to using a single pipe (termed as the **mono-pipe configuration**, Figure 2a). It is easy to proove that the tri-pipe configuration is more effective than the mono-pipe configuration.



(a) Mono-pipe configuration

(b) Tri-pipe configuration

Figure 2. Cross-sectional view of the mono-pipe configuration and the tri-pipe configuration.

Assume that both configurations have the same cross-sectional area A, and that the members are solid cylinders, each pipe of the tri-pipe configuration has a diameter d and the pipe of the mono-pipe configuration has a diameter D. We can express D in terms of d as $D = \sqrt{3}d$.

By calculation, we obtain the moment of inertia I of both configurations as $I_{\text{tri}} = \frac{19}{64}\pi d^4 > I_{\text{mono}} = \frac{9}{64}\pi d^4$ [2]. By adopting the tri-pipe configuration, the moment of inertia is increased by approximately 111%, which is a significant improvement. This shows that the tri-pipe configuration has a larger critical load.

Furthermore, by using Equation 2, we obtain the radii of gyration: $k_{\text{tri}} = \frac{\sqrt{57}}{12}d > k_{\text{mono}} = \frac{\sqrt{3}}{4}d$. k_{tri} is approximately 45% larger than k_{mono}. This shows that the tri-pipe configuration is more resistant to buckling and compressive stress.

2.1.2 Paper-to-Paper Connection Structure

After measurement, it was found that the longest side of one piece of newspaper is approximately 600 mm. It is therefore impossible to fabricate a pipe with one single continuous piece of paper, and joining two pieces of paper is inevitable.

Two solutions were proposed to join pieces of paper for extending the length:

1. By **overlapping** pieces of newspapers alternatively; or
2. By placing two pieces of newspapers **side-by-side** and fixing them together with adhesive tape.

By comparison as illustrated in Table 1, the overlapping method was chosen to form the pipes as it is more performant on the assessed aspects.

2.2 Supporting Members

The supporting members connect the adjacent slanted major members. They are supposed to hold major members in place through the tensile force generated by the strong and long paper fibres.

Since they do not bear compressive load but only tensile load, buckling was not a concern. Therefore, the supporting members were simply made of a single pipe.

2.3 Restraining Piece

Since the major members are slanted, it was projected that the vertical compressive load would decompose into

Table 1. Compaison of the overlapping and side-by-side connection methods.

Aspect	**Overlapping**	**Side-by-side**
Load Distribution	Across all layers via friction and interlocking	Concentrated at the joint
Strength	$\propto$ number of layers $\times$ strength of one layer	$\propto$ adhesive shear strength
Stiffness	High due to composite action	Low due to tape not structurally integrated

downward vertical component and horizontal component directed away from the centre at the end of the slanted members. When the horizontal component is larger than the friction between the major members and the ground, the members would start to slide away from the centre, which would lead to most of the load being redistributed to the central member.

To restrain the horizontal movements of the members, the group has designed a restraining piece. The piece was made of several layers of continuous newspapers folded into a belt-like shape, which was then wrapped around the base.

Due to its continuous nature, the full potential of the paper fibres could be utilised to provide tensile strength. It was expected that when the members start to slide, the restraining piece would be able to counteract with its tensile strength.

3. First Trial

The model for the first trial was built with the following specifications:

1. **Weight and Height**: Within the limits.
2. **Newspaper Used**: Mainly the *Sing Tao Daily* (星島日報).
3. **Adhesive Tape Used**: Scotch Magic Tape (3M).
4. **Design**: The supporting members did not observe the design as described in section 2.2. However, those members did not have significant impact on the analysis of the model.

The model is shown in Figure 3a.

3.1 Results

The first model failed to withstand a minimum load of 500 N. The model was able to withstand a load of 480 N before deformation occurred. It was observed that buckling occurred at the major members at a short instant after the load was applied (as shown in Figure 3b). Of all the members, the three external slanted members were the first to buckle, while the central vertical member experienced the most deformation.

3.2 Rationale of Failure

After inspection of the failed model, the group has identified three major reasons that contributed to the failure of the model.

3.2.1 Low Density of the Major Members

All of the major members in the model were fabricated without aid of any tools. The newspaper pipes were rolled by hand, leaving large gaps between the layers of newspapers. This resulted in a low density of the major members.

To quantitatively analyse this issue, the gap-interleaving members can be approximated as a hollow cylinder of inner radius r and outer radius R and compared with a solid cylinder of radius R. The moments of inertia of the two models are $I_{\text{hollow}} = \frac{\pi}{64}(D^4 - d^4)$ and $I_{\text{solid}} = \frac{\pi}{4}D^4$. It is trivial to see that $I_{\text{hollow}} < I_{\text{solid}}$. By Equation 1, the critical load of the hollow cylinder is less than that of the solid cylinder. This shows that the hollow cylinder is more prone to buckling.

Furthermore, during fabrication, the newspapers might have been rolled unevenly, resulting in folds and wrinkles on the surface of the pipes. This further reduce the stability of the major members.

3.2.2 Presence of Weak Points at Paper-to-Tape Junctions

While applying the adhesive tape on the pipes, the surfaces of the pipes were not thoroughly covered, resulting in surfaces that were exposed to air. This led to inconsistent surface stiffness as surfaces with adhesive tapes are stiffer than those without. When under compressive pressure, the joints at which surfaces with discontinuous stiffness meet are prone to buckling.

3.2.3 Imbalance of Load Distribution Due to Mismatched Lengths of the Slanted Members

The group was not rigorous in measuring the lengths of the slanted members. Prior to the first trial, the group has noticed that the structure was unable to support itself evenly on all columns, and that one of the slanted members remained not in contact with the ground. This resulted in an imbalance of load distribution. During compression, the stress was concentrated on the central member and the slanted members that were in contact with the ground, while the remaining member acted as a Zero Force Member. As a result, some of the members were subjected to stress that exceeded the designed limit and buckled, which is consistent with the observation.

3.3 Measures Taken for Improvement

In order to address the issues identified in the first trial, the group has taken the following measures to improve the model in fabrication of the model for the final trial.

3.3.1 Rolling the Members with Tools to Increase Density and Avoid Defects

The group has used thin cylindrical wooden rods to assist in rolling the newspapers into pipes. The rods were placed on the newspapers while rolling, such that the newspapers could bind tightly and uniformly, reducing gaps between layers and wrinkles on the surface. The rod was then removed after the pipe was rolled. This method streamlined pipe production and improved the strength of the major members.

(a) Before **(b)** Immediately after failure

Figure 3. The model before and after the first trial.

(a) Before **(b)** Immediately after failure

Figure 4. The model before and after the final trial.

3.3.2 Apply Adhesive Tapes Thoroughly and Effectively

The group has carefully applied the adhesive tapes on the pipes to ensure that the entire surface of the pipes were covered evenly with tapes. This is projected to increase the stiffness and uniformity of the surfaces.

In addition, the group has also applied more tapes at the top and bottom of the pipes as these are the areas that are subjected to the most stress and need to be reinforced.

4. Final Trial

The model for the final trial was built with the same specifications as the first trial, except that the design of the supporting members was changed to observe the design as described in section 2.2. The model is shown in Figure 4a.

4.1 Results

In the final trial, the model was able to withstand a load of 767 N, which satisfied the requirement of the practical work and was a significant improvement from the first trial.

As opposed to the first trial, buckling occurred almost simultaneously at all members when the critical load was approached. This displayed that the load was distributed uniformly throughout the model, showing that the alterations made to the design was effective.

4.2 Reflection and Possible Improvements

Despite the success of the final trial, the group has identified possibility for further improvements.

From the deformed model, it was observed that buckling started but did not progress significantly until the supporting members dislocated from the major members. It has shown that the supporting members were indeed effective in providing stability and the reinforcement of which could have further increased the critical load.

Additionally, the group has observed that the restraining piece that was expected to restrain horizontal movements of the major members almost bore no load during both trials. This has shown that the group has overestimated the magnitude of the horizontal movements and underestimated the friction between the major members and the ground. Much of the weight could have been saved or diverted to other components of the model if the restraining piece was not used.

5. Conclusion

This practical work has encouraged the group to consolidate and apply the knowledge learned in class, and to explore further beyond the scope of the course. THe group has gained a deeper understanding of the principles and theorems in the field of structural and material mechanics. The group has also earned precious experience through the process of designing, trial-and-error, observing, and reflecting. The practical work has also offered an opportunity for the group to communicate effectively.

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