AC 2008-374: USING STRUCTURAL DISTILLATION IN THE AVOIDANCE OF ANALYSIS PARALYSIS

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Emphasizing structural distillation for the avoidance of 'analysis paralysis'.

Introduction

ABET requires student engineers to have the 'ability to design and conduct experiments and to analyze and to interpret data using **modern engineering tools**'. This along with industry demands means that the student engineer is now expected to be competent in at least one CAD package and perhaps one finite element stress or fluid analysis package. Exposure of undergraduate engineers to powerful analysis packages however, can in many cases be compared to viewing the dessert tray before the main course arrives, it can ruin the meal. As such running through pre-defined engineering analysis examples and seeing the capabilities of the packages leaves the novice convinced that the use of such software is indeed far superior to any 'hand calculation' technique, and as such is the only way to undertake any future analysis work. The reality however, quite often means that when future work arrives the novice falls into one of the following 'traps'.

First, the geometry and application of the part, assembly or system is so unlike any modeled before that the user does not know where to start. (E.g. How to mesh, how to apply loads, restraints etc.) A state of 'analysis paralysis' has occurred.

Secondly, in spite of the first trap and because of inevitable work pressure, an analysis is undertaken which, with the aid of new 'user friendly' application software allows the user to 'muddle' his or her way through the numerous menu options. The software then obligingly produces the high quality presentation 'results' that can, without an inside understanding of the problem, appear very believable. The 'gaffer dazzler' (Slang for boss impressing picture !) is born and the old adage of 'garbage in, garbage out' has re-appeared in its new visually more impressive form.

The suggestions discussed in this paper, describe teaching techniques used at the author's institute, that continually stress structural distillation, sketching, estimation, experimentation and the central importance of approximate hand calculations as an essential part of the design process. Examples of some of the work undertaken at the author's institution during an introductory design course are used to show how powerful analytical packages can ultimately be used with confidence rather than blind faith.

A concern about the use of 'modern' analysis software..

Foley (2007) discusses the 'big picture' aspects of launching into a design sequence, emphasizing that design is just one of a number of options open to the engineer. It is invariably expensive, time consuming and requires the largest commitment of all the solution methods available. This paper assumes therefore that the preliminary 'situation appraisal' work has been completed and a design process has been decided as the best way forward. The focus in this paper is to help students avoid some of the unique 'computing' pitfalls that have availed the modern engineer.

Unlike politics where simple problems are often needlessly overcomplicated, engineers generally pride themselves in taking complicated problems and reducing them to their simplest constituent parts before analyzing and producing solutions that can then be extrapolated with minimum modification to produce viable solutions to the original more complex problem. The process whilst robust does not always work but even in failure there are often valuable insights into what the true first order contributors are and also the nature of often overlooked component interactions.

In recent years a 'watershed' situation has come about with the advent of ever more powerful engineering application software. Whilst software per se is not new, it has evolved from being coded by the engineer end users themselves or programmed very specifically for one application into a whole new 'beast'. Modern software packages require a larger audience and more user friendly features if they are to make the return on investment needed for a commercial enterprise. To wit packages demonstrate the following :-

1. Generality of application. E.g. A typical commercial CAD packages can now basically undertake 3D modeling of anything from a transistor to a 747.
2. Stress and CFD/thermal analysis packages are capable of analyzing anything the CAD system can model. Indeed many CAD packages come with these analytic capabilities built in.
3. In order to appeal to the largest possible audience packages have become increasingly intuitive often making assumptions or allowing the user to use default assumptions without requiring the user to have an appreciation of the consequences of such assumptions.
4. The output of such packages is in a format that the current student generation can associate with. i.e. There is an emphasis on 'video game' type graphics. Animation of flows, deformations, stresses etc. A focus is on the dynamic qualities of results rather than on the consequences of absolute values obtained. An example of how such an emphasis can result in error was witnessed by the author in a PhD defense. The candidate produced very real compressor stall vortices in a regime where no such vortices should have formed. The very convincing fluid animation turned out to be a result of a coding error rather than any real physical phenomena.
5. A dependence of use is formed by the user. The time and intellectual investment made in the package as well as the misleading preciseness of predictions results in users being reluctant to use what they see as the cruder approaches of hand calculation or simplified modeling techniques. Consequences of such dependence is that when, as inevitably occurs, a problem appears that does not fit into the capabilities of the package, the user is at a dead loss at how to progress to a solution or alternatively shoe horns the problem into a form that can be solved but which does not accurately reflect the original problem.

Avoidance of Analysis Software Problems and generally good design practice.
Pre-Analysis Analysis :

This paper advocates a process whereby before any software is assigned to a task the student engineer is required to generate 'ball park' solutions using only pencil and paper. To make students proficient at this, design courses and then numerous core academic courses should continually push the following skills:-

1. Sketching

In the process of tackling homework/exam or design problems students should be required to sketch the physical situation being analyzed. Typically this should be a minimum half page and should be orthographic or isometric for mechanical parts, and a quality schematic for process or system type problems. The sketch should be clear and well annotated. Good annotation, particularly of variables can save the student's time in defining symbols etc in the text. As an added benefit the sketch makes grading assignments much easier as the instructor immediately has a measure of the students understanding of the physical nature of the problem and of what variables etc they have deemed most important. To further add incentive a proportion of the grade should always be assigned to the sketch. It as also always worth pointing out that sketching is a true international language and also a primary tool in innovative design where its speed and fluidity of use as well as the universal availability of a pen and paper make it the champion of the 'Eureka' moments.

2. Structural Distillation

Samuel and Weir (1999) describe structural distillation as 'the process of decomposing relatively complex engineering structures into elementary components possessing readily available mathematical models'. While their text focuses on mechanical components such as links, columns, beams, shafts, pressure vessels, torsion bars etc the process is equally applicable to non-structural analyses such as electrical systems, thermo-fluid systems etc. (e.g. For thermodynamics it is commonplace to break down a complex power plant into simpler components such as pumps, turbines, combustion chambers etc.)

The skill to be developed in student engineers is not only the act of distillation but also in the level of distillation. Too much distillation and the results become meaningless, too little distillation and 'analysis paralysis' sets in whereby no readily available mathematical model exists and progression to a solution halts.

As an instructor teaching structural distillation it is therefore imperative in the early stages of a course to pick examples that are readily amenable to the process. It is important to build confidence in students before unleashing them on ad hoc problems.

Appendix A details some typical structural distillation exercises used in a sophomore design course at the author's institution.

3. 'Guesstimation' and the practice of carrying assumptions/uncertainties through basic calculations.

Arguably the real challenge in teaching true engineering design courses is in the introduction of open ended or loosely defined problems. Nicolai (1998) provides a snap shot of industry's take on engineering design education and goes as far as to say that open ended problems are the 'only type that exist' in industry. Frequently, however students will have only encountered traditional well poised problems and will, to all intents and purposes, rebel against this new format. It is not uncommon in the early stages of teaching a design course to meet open hostility from high achieving students who have mastered the exam techniques of tackling the traditional assignments. This new 'wooly' format is unfamiliar and flies in the face of what they expect in an assessed course. Instructors are therefore encouraged to use real life problems and industrial examples to illustrate how, in reality; this type of problem is the norm rather than the exception.

To enable analytic progression of distilled problems it is therefore encouraged that students be required to make and justify assumptions regarding such things as loads, operating life, factors of safety etc. Material properties and other such easily referenced data should not be assumed but rather referenced and used accordingly. Assumptions while encouraged should be restricted to data that is somewhat subjective or not easily found or referenced.

Armed with simple models and a host of assumptions students are then encouraged to undertake calculations to quantify variables of interest. Multiple calculations using a range of extreme values and also iterative type calculations should be encouraged. Once final estimates have been arrived at discussion of the results as well as the limitations in their applicability should be provided. Conclusions of the pre-analysis should also include a recommendation for further work including details of how computer aided design software could now be utilized. Interestingly it has been the author's experience that on numerous occasions, particularly where cost rather than safety is an issue, the preliminary analysis is often sufficiently detailed that there is no longer any requirement for, what was initially thought to be indispensible, computer analysis.

4. Experimentation and Testing

Finally the role of experimentation as part of any design process must be emphasized. (ABET outcome (no.2)). Reliance on the absoluteness of computer analyses often leads the engineer to forget that the computer really is only performing a more highly refined version of the distillation calculations described above. It is essential therefore, particularly in cases where public/user safety are concerned that appropriate testing be undertaken. Such testing should be expected to provide feedback that will influence the final design and as such this should be scheduled into the project at a very early stage. The importance of uncertainty analysis with regard to experimental results should also be emphasized and no results should ideally be presented without their associated uncertainty attached.

Too many times the design and fabrication takes up so much of a course that this stage is often only paid lip service.

Design Course Assignments/ Exam questions .

Numerous papers relate to the assessment of ABET design outcomes 1,2 and 3 but far fewer give instructional guidelines as to how to undertake the teaching that will equip students to demonstrate those skills. Felder & Brent (2003) state ' the tacit assumption is that determining whether or not students have special skills is harder than equipping them with those skills'.

To assist the instructor in testing and developing the above skills the following is a suggested format for assignment and exam questions suitable to a design type course. This would of course only form part of a design course where project work would probably form more than the lion's share of the assessment. At the author's institute these type questions are found in all four of the formal exams in a Sophomore introductory Engineering course. These exams comprise approximately 50% of the course grade. The first three exams are intended to be used not only for assessment purposes but also as instructional tools in post exam review sessions.

The format for a typical open ended design problem would comprise the following :-

i) Briefly state the real life scenario where the design solution is required.
ii) Describe a crucial design variable that needs to be estimated. (e.g. A pipe diameter, plate thickness, flow rate etc.)
iii) Provide sufficient background information to allow valid assumptions to be made as far as load cases, operating procedures and material selections are concerned.
iv) Provide relevant equations for the level of the course. (i.e. These should have been encountered by the students in prior academic courses. If equations from two or more different subjects can be used then all the better. (e.g. Bending moment equation, Ohms Law, Bernoulli equation etc.) It is not really the intention of a design course to be teaching new academic material but rather exercising the use of those skills in a design process.
v) Require comment/discussion on the physical, safety, cost implications etc of the variable calculated.

If the problem can be set such that iteration is required then this will also enhance the exercise. Appendix B is an example of such a sample question.

Conclusion

Engineering analyses packages are without doubt an invaluable part of the modern engineer's armory. The ease of use of such packages combined with the ever more 'impressive' post processing capabilities have seen a trend whereby engineers, particularly more junior engineers believe these packages can be used in isolation and their predictions believed in with absolute confidence.

This paper re-emphasizes the importance that pre-analysis analysis or 'guesstimation' must be given if catastrophic mistakes are to be avoided and the engineer is to retain a 'feel' for the physical factors at play in any given analysis. It is also pointed out that post analysis testing is also suffering and it too should also be continually reiterated as essential to downstream consumer safety.

References

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- Samuel,A and Weir, J (1999) . "Introduction to Engineering Design." Butterworth Heinemann. ISBN 0750642823
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Appendix A Some structural distillation examples.

Example 1 : Automobile Tow Hook.

Figure 1a is a hook with a canvas strap used as part of an automobile towing system. The hook was quickly created in SOLIDWORKS and then analyzed using COSMOS express to produce a stress distribution shown in figure 1b. When asked to comment on the figure for reasonableness or to suggest how could the stress levels be reduced students had great difficulty in going beyond the comment ‘ this is what the computer says so it must be right’.

A structural distillation shown in figure 1c was then undertaken using tools that students had already seen in a basic statics course. The hand calculation results gave a peak stress of 12245 p.s.i . i.e. Within 3% of the computers prediction. It was emphasized that neither answer was necessarily correct and that as these are both only model predictions and only some strain gage attachment and experimentation would ultimately give us even more confidence in the true answer. However the two results combined gave a much higher confidence level in the magnitude of the stress prediction. Also given was a prediction for the safety factor and it was generally agreed that our overall comfort factor in letting the public use this product is enhanced by undertaking the structural distillation.

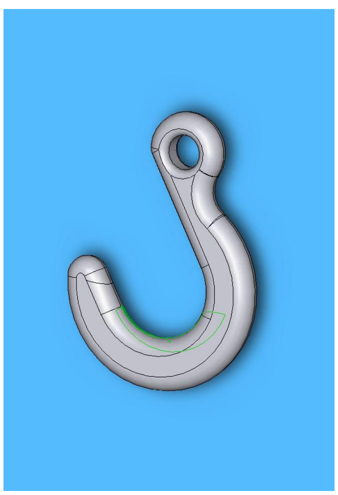

Figure 1.a CAD Model

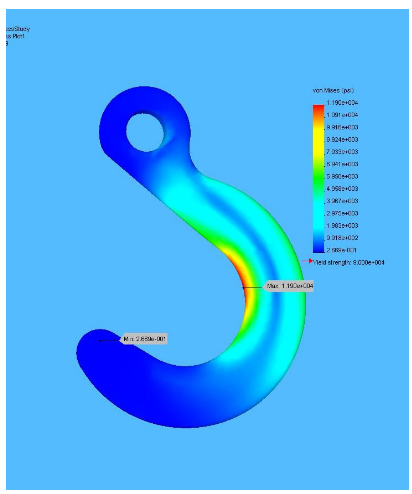

Figure 1. b COSMOS express Stress prediction

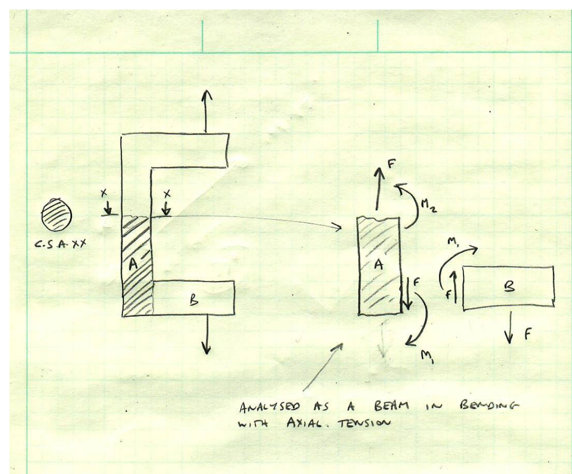

Figure 1.c Structural Distillation

Example 2. Basement Staircase.

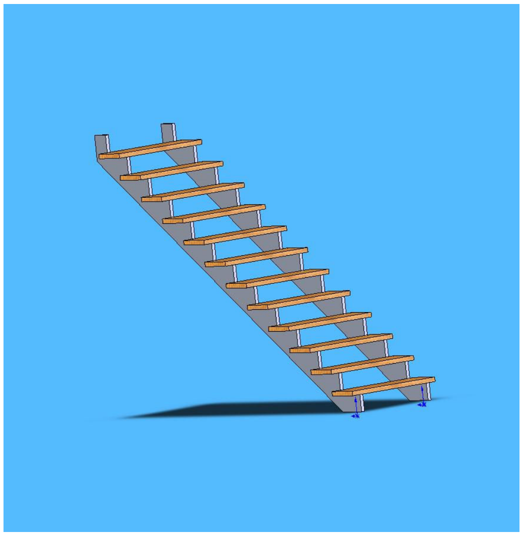

Figure 2a : 3D SOLIDWORKS model
Of entire staircase assembly

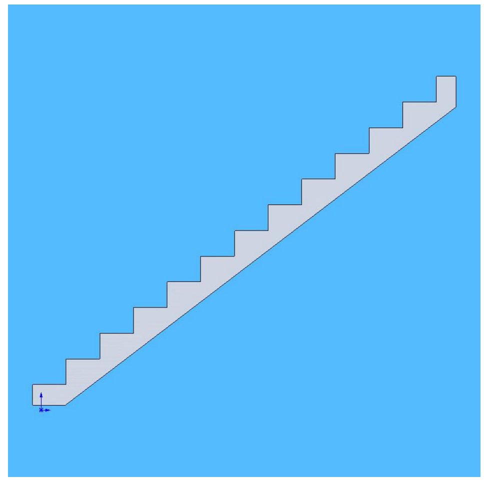

Figure 2b: 3D Model of Stringer.

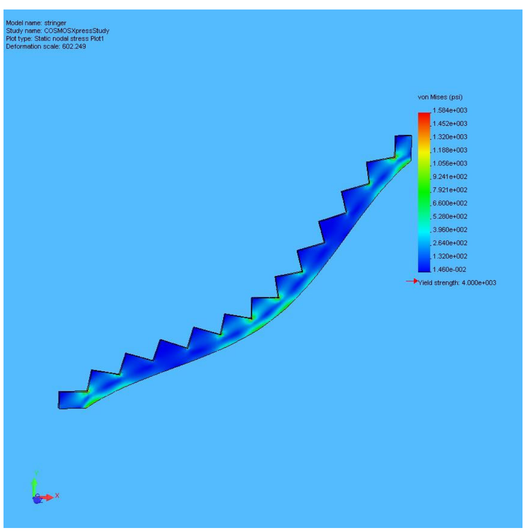

Figure 2c: COSMOS EXPRESS
Stress analysis

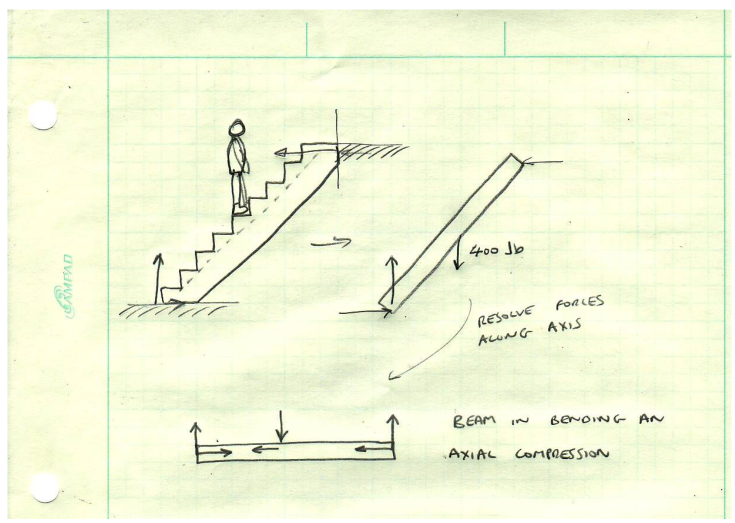

Figure 2d : Structural distillation of problem

In this example, despite the sweeping simplifications, the maximum stress in the stringer was found to be within 5% of that shown with the stress package.

Appendix B: Sample Engineering Design Question.

Q.1. Engineering Guesstimation.

You are required to design a new cantilever arm to support the winch for a Coast Guard Helicopter. The arm is going to be made out of hollow aluminum or steel tube and a sketch of the arm installation (Fig.1) and cross section (Fig.2) are shown below.

Set the real scenario !

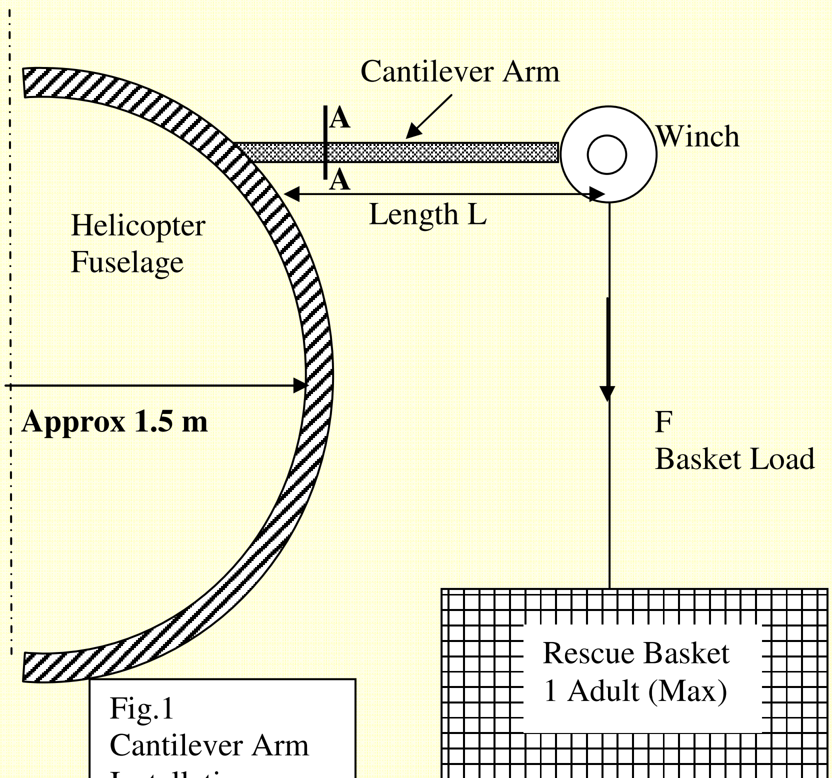

Fig.1
Cantilever Arm
Installation

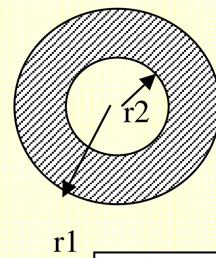

Fig.2
Cantilever Arm
Cross-section
A-A

Provide theory seen before !

The maximum tensile stress in a cantilever beam can be calculated from the following equation :-

$$\sigma_t = \frac{M_{\max} \times r_1}{I} \qquad \text{.............................(1)}$$

Where r_1 is the outer radius of the tube,
M_{max} is the maximum bending moment given by the product of the Basket Load x Arm Length i.e.

$$M_{max} = F \times L \qquad \text{......................(2)}$$

And I is the second moment of area given by

$$I = \frac{\pi}{4} \times \left(r_1^4 - r_2^4\right) \qquad \text{..........................(3)}$$

(r_2 is the inner tube radius.)
Using S.I units answer the following :--

Make assumptions !

(a) Make and justify assumptions about the load carried (F) in lbs. Estimate the length of the cantilever arm (L) in feet and then calculate the maximum bending moment (ft lb) experienced at the base of the arm using Equation (2).

(6 marks)

(b) Decide on steel or aluminum for your tube. Justify your choice.

Note : (Unit conversions will be required)

Material	*Yield Stress*	*Density*
Steel	400×10^6 N/m^2	8000 kg/m^3
Aluminum	200×10^6 N/m^2	2500 kg/m^3

(2 marks)

(c) Based on the kind of operating environment this arm will experience justify a suitable factor of safety for your design? Increase your maximum bending moment by this factor of safety. **(3 marks)**

Carry assumptions through calculations.

(d) Guesstimate a suitable pipe outer diameter and inner diameter. r_1 and r_2.(inches) Use equation 3 to calculate a second moment of area based on your estimated pipe radii. **(4 marks)**

(e) Use your maximum bending moment, calculated value of I and outer diameter r_1 to calculate the maximum tensile stress experienced by your arm. (Equation 1) Is this acceptable based on the material properties given in (b) ? **(6 marks)**

Produce results and discuss.

(f) Repeat steps (d) and (e) two more times to improve your design.(i.e. Utilize the strength of the material whilst safely remaining below the limit.) Sketch the final cross section of your tube with dimensions r_1 and r_2 clearly labeled. Discuss your results.

(8 marks)