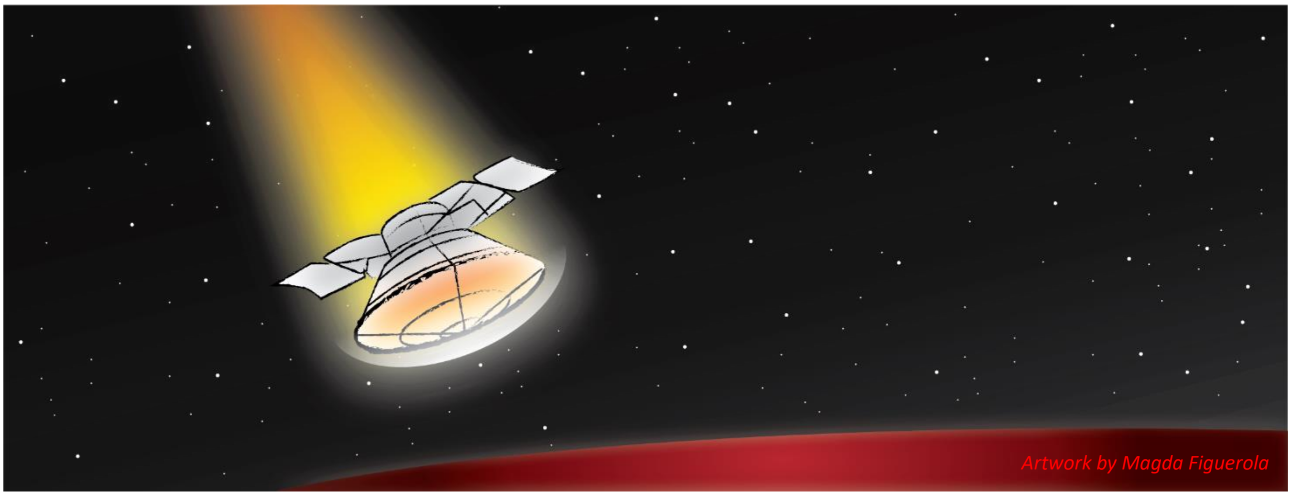
GRANTA
TEACHING RESOURCES

ADVANCED INDUSTRIAL CASE STUDIES

Mars Lander Heat Shield

Claes Fredriksson and Luca Masi
Granta Design, 300 Rustat House, 62 Clifton Rd, Cambridge CB1 7EG, UK

First published June 2017



Contents

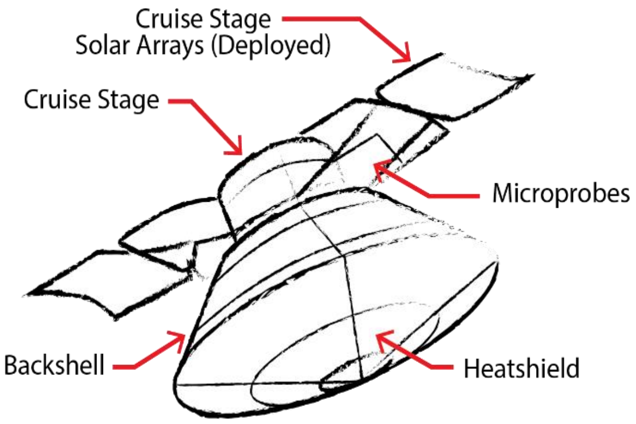
Summary

This case study is designed to engage students by exploring an exciting and contemporary topic; space exploration. It shows how mechanics/strength of materials can be combined with systematic material selection methodology, and demonstrates how you can visualize up to four material indices in parallel.

Specifically, we investigate how CES EduPack can be used to select a material for the heat shield of a Mars lander entering the Mars atmosphere. Coupling lines are used to find high-performance lightweight material candidates for this demanding application, subject to multiple conflicting constraints. Light metal alloy options are compared with composites and sandwich structures using the software tools.

1. Introduction

This is an example of how advanced but engaging case studies can be used to stimulate the interest of engineering students. There is currently enormous interest and activity around Mars exploration and human travel to that planet. The conditions on Mars must be investigated, and in order to do so, Mars landers carrying equipment, such as vehicles (rovers), need to be launched from earth and travel through space with the mission touching down safely in the Mars landscape. Currently, such attempts are made, for example, within the European/Russian *Exomars* programme. Some previous attempts for soft landings has succeeded as early as 1971 (Mars3).

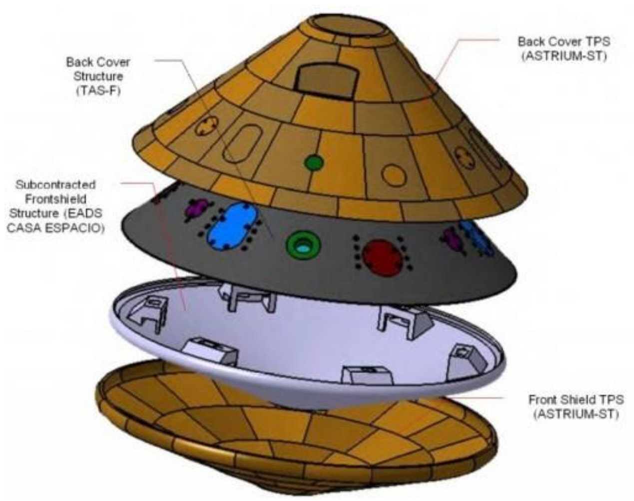


As the vessel approaches the surface of 'the red planet', one of the challenges is to pass through the atmosphere at an initial speed of around 21 000 km/h (13 000 mph), gradually slowing down while heated by friction. Although the Mars atmosphere (CO_2 and methane) is thinner than the Earth's, the frontal surface temperature of the heat shield is considerable and needs to be reduced from some 1750°C down to 170°C at the inner structure during the descent. Key events and velocities during the retardation are shown below [1].

Altitude		Speed		Event
121 km	75 mi	21,000 km/h	13,000 mph	Enter atmosphere
45 km	28 mi	19,000 km/h	12,000 mph	Peak heating
11 km	6.8 mi	1,700 km/h	1,100 mph	Parachute deployed
7 km	4.3 mi	320 km/h	200 mph	Lower heat shield eject and doppler radar activated
1.2 km	0.75 mi	240 km/h	150 mph	Upper heat shield and parachute ejected
1.1 km	0.68 mi	250 km/h	160 mph	Retro-rockets on
2 m	6.6 ft	4 km/h	2.5 mph	Retro-rockets off
0 m	0 ft	10 km/h	6.2 mph	Touch down on crumple bumper underneath spacecraft

To withstand the high temperatures, the lander needs to be equipped with a Thermal Protection System (TPS). This is a heat shield, approximately shaped as a spherical cap that needs to bring down the frontal surface temperature during the descent by around 1600°C. The TPS of the Exomars lander is comprised of 90 tiles with seven different tile shapes and thicknesses, each consisting of outgassed *Norcoat Lige* bonded with silicone glue. Norcoat [2] is an elastomer material combining a cork powder and phenolic resin ablator, applied at thicknesses of 8 to 18 millimeters, depending on the areas of the heat shield. Norcoat keeps the internal temperature of the underlying material below 170°C and further insulation reduces the internal temperatures of the lander to around 50°C. The heat shield is ejected before the actual landing, but needs to sustain its integrity until then.

The structural components are made of Aluminum sandwich structures with Carbon Fiber Reinforced Polymer (CFRP) skins. The surface platform has a mass of about 300 kilograms and consists of a crushable structure on its bottom side. The processes occurring at the heat shield material include charring, melting and sublimation on the one hand, and pyrolysis on the other. Pyrolysis creates the gases that are blowing outward and create the desired blockage of convective and catalytic heat flux. The radiative heat flux is reduced by introducing carbon compounds into the boundary layer gas which make it optically opaque.



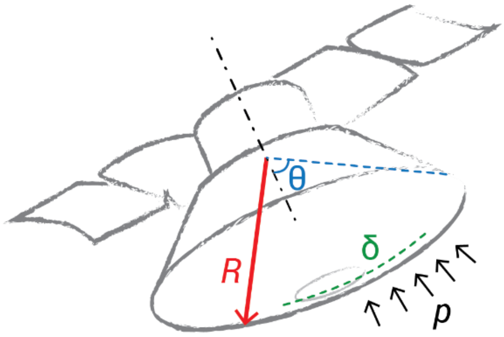
/
Image: ESA (CC BY-SA 3.0 IGO)

The US Mars Science Laboratory (MSL) spacecraft is protected during the intense heating environment as it enters the Mars atmosphere by an Ames-developed Phenolic Impregnated Carbon Ablator (PICA) [3]. This is a thermal protection material that won the 2007 NASA Invention of the Year. PICA is a material for heat shields only slightly denser than balsa wood, designed to protect a spacecraft during fiery entry into planetary atmospheres. Prior to MSL, the Stardust sample return capsule used a PICA heat shield.

2. What is the Problem?

We will approximate the shape of the lander heat shield with a spherical cap. Our main objective is to minimize mass of the structural part (not the thermal barrier), subject to constraints. There are four material indices (derived below) that may be useful. These reflect *constraints* for:

- **Deflection** (stiffness)
- **Buckling** (stiffness)
- **Strength** (yield)
- **Damage** (fracture)



They will help us to explore the mechanical problem in a *property chart*. We use standard equations from mechanics and strength of materials to support this goal (see, *e.g.,* Roark [4]). In the selection part, we consider only the materials included in the *Aerospace* data-table, which can be viewed as an additional constraint. A final constraint (thermal) is that the maximum service temperature is set to be at least 170°C.

For the ***objective***, to minimize the mass, *m*, for a spherical cap, we consider the top part of a thin sphere of radius *R* and thickness *t*. The density is denoted ρ and the half-central angle θ. The mass is given by:

$$\boldsymbol{m} = 2\pi \boldsymbol{R}^2 (1 - \cos\theta) \boldsymbol{t\rho} \qquad \text{[eq. 0]}$$

Since we will treat thickness as the design variable, we eliminate *t* to enable a free material choice. Expressions for ***t*** to substitute into eq. 0 can be derived for each of the constraints listed above.

The case study has been inspired by an exercise prepared by Dr Tom Dragone, Orbital Science Corporation, and Professor Kevin Hemker of the Engineering Department, Johns Hopkins University. Some of the input data and the derivations of material indices draw from their scenario. We will use *R*=1.8 m and θ=35°.

A. Deflection

From basic equations [4] defining deflection, δ, caused by external pressure, *p* (as shown in the schematic illustration above), the material thickness can be derived as:

$$\delta = \frac{pR^2}{2Et} \le \delta_{max} \qquad \Rightarrow \qquad t \ge \frac{pR^2}{2E\delta_{max}} \qquad \text{[eq. 1]}$$

Where *E* is the Young's modulus. Using this equation to eliminate the free design variable, *t*, from the objective, eq. 0, results in an expression that represents a lower limit to *m*:

$$m_1 \ge \pi \frac{p}{\delta_{max}} R^4 (1 - \cos\theta) \frac{\rho}{E}$$

In order to minimize *m*, we thus need to find a material that minimizes the material index: $\boxed{M_1 = \frac{\rho}{E}}$

B. Buckling

The cap is under compressive load from the atmospheric resistance and must withstand stress up until the critical pressure [4]:

$$p \le kE\frac{t^2}{R^2} \qquad \Rightarrow \qquad t \ge \sqrt{\frac{p}{kE}}R \qquad \text{[eq. 2]}$$

The parameter *k* can be calculated from an empirical relationship specified elsewhere (see ref 4, Table 15.2) and depends on the geometry of the heat shield. It may also include a safety factor, S_f (typically 1.5 for aerospace applications). Here we put S_f=1. If eq. 2 is used to eliminate the design parameter in eq. 0, then:

$$m_2 \ge \frac{2\pi}{\sqrt{k}} \sqrt{p} R^3 (1 - \cos\theta) \frac{\rho}{\sqrt{E}}$$

In order to minimize *m*, we now need to minimize the material index: $\boxed{M_2 = \frac{\rho}{\sqrt{E}}}$

C. Strength

To express the strength constraint, the regular equation for the lateral stress in a sphere under external radial pressure can be used:

$$\sigma = \frac{pR}{2t} \le \sigma_y \qquad \Rightarrow \qquad t \ge \frac{pR}{2\sigma_y} \qquad \text{[eq. 3]}$$

Substituting this expression into eq 0 to eliminate *t* results in a lower limit of the mass:

$$m_3 \ge \pi p R^3 (1 - \cos\theta) \frac{\rho}{\sigma_y}$$

In order to minimize m this time, we need to minimize the material index: $\boxed{M_3 = \frac{\rho}{\sigma_y}}$

D Damage

The damage criterion is connected with the fracture toughness K_{Ic}. Substituting the yield stress at the critical crack length, using eq. 3, gives a requirement on *t*, to avoid crack propagation:

$$\sigma\sqrt{\pi a_c} = \frac{pR}{2t}\sqrt{\pi a_c} \le K_{Ic} \qquad \Rightarrow \qquad t \ge \frac{pR\sqrt{\pi a_c}}{2K_{Ic}} \qquad \text{[eq. 4]}$$

Substituting this expression into eq. 0 to eliminate *t* finally results in the following lower limit of the mass:

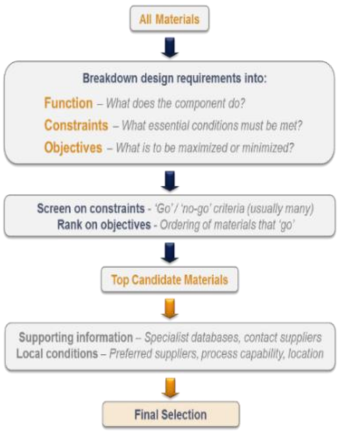
$$m_4 \ge \pi^{3/2}\, p\sqrt{a_c}\,R^3(1-\cos\theta)\,\frac{\rho}{K_{Ic}}$$

In order to minimize *m* in this last case, we thus need to minimize the material index: $\boxed{M_4 = \frac{\rho}{K_{Ic}}}$

3. How to select aerospace materials in CES EduPack

To investigate potential materials, we follow the rational selection methodology by Ashby *et al.* [5], illustrated schematically in the diagram below. The ***Function*** will be to resist the mechanical forces during the entry into the Mars atmosphere. As mentioned above, we will use Level 3 of the ***Aerospace database*** and add the ***thermal constraint*** of *Maximum Service Temperature* > 170°C. The four ***mechanical constraints*** are integrated into the objective (minimize mass) resulting in the material indices derived above.

The selection is started by clicking **Chart/*Select*** in the main toolbar and choosing ***Aerospace materials***. This results in an initial subset of more than 700 materials, mainly metal alloys and composites. The subset of all Aerospace materials is plotted in two coupled property charts. One with M2 *vs* M1 and the other (by clicking Chart/Select again) with M4 *vs* M3. To plot material indices on the axes, the *advanced* option of the ***Chart*** stage is used.



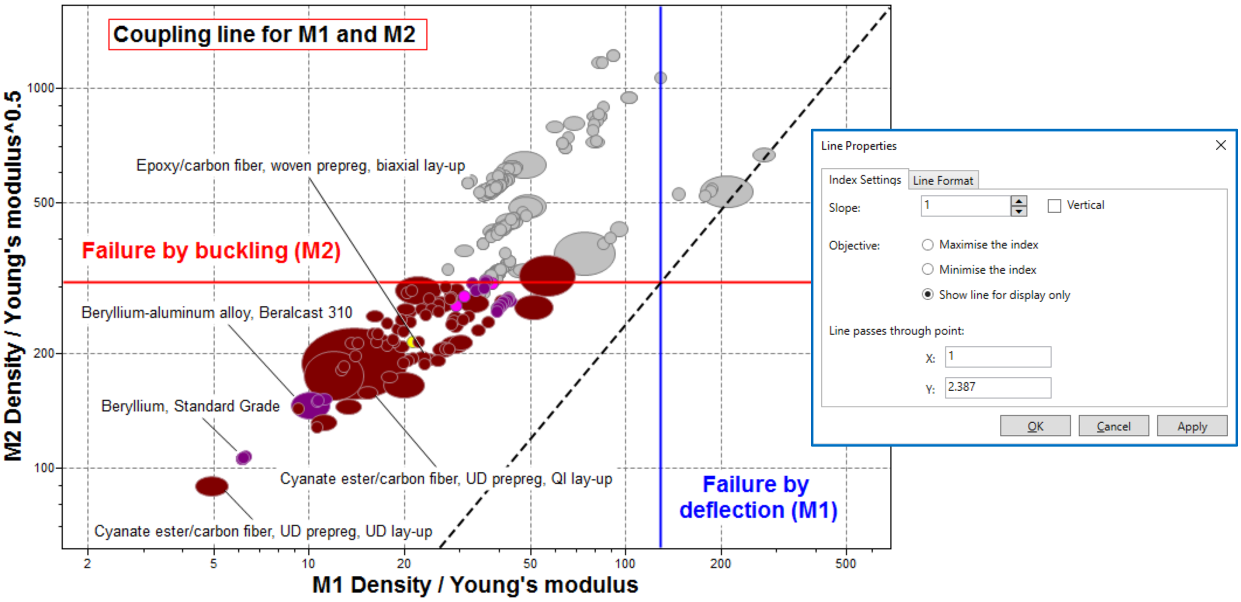
The first two material indices represent stiffness-related constraints that limits the lightweighting efforts. A selection line can be drawn for each index (see chart below; red for buckling and blue for deflection) and the best materials for each job is the one with the lowest value of M as its selection lines are moved towards zero. However, a material that performs well in one index, allowing a low value for the mass, may still perform poorly in the other index, preventing the mass to be reduced. That's why we use selection coupling lines.

4. Result

An important point in lightweighting is that the lower limits in mass according to all constraints should match, so that none of the indices fail before the other. In the first case, $m_1 = m_2$, or, put more clearly, the point where the material fails simultaneously by both constraints. This compromise can be represented by a coupling line. The coupling line can be expressed in terms of M1 and M2 (at the limit of equality):

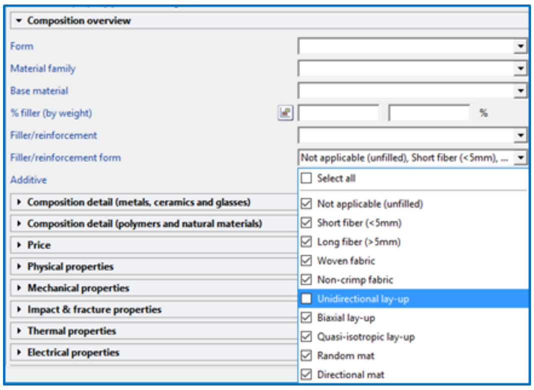
$$\left.\begin{aligned} m_1 &\ge \pi\frac{p}{\delta_{max}}R^4(1-\cos\theta)M_1 \\ m_2 &\ge \frac{2\pi}{\sqrt{k}}\sqrt{p}\,R^3(1-\cos\theta)\,M_2 \end{aligned}\right\} \qquad m_1 = m_2 \quad \Longrightarrow \quad M_2 = \underbrace{\frac{\sqrt{p}\sqrt{k}R}{2\cdot\delta_{max}}}_{C_c} M_1$$

We have used p=0.000041368 GPa (6 psi), k=0.17, and δ=0.001 m, to get a coupling constant: C_c = 2.387



The best performing materials, so far, are the ones with the lowest index values, within the two selection lines crossing at a point on the coupling line. The coupling line is a display line with slope 1 (because of the logarithmic axis scales) and the position, determined by C_c = 2.387, is fixed by setting line properties (*e.g.*, by right-clicking this line), specifying a point with the coordinates (1, 2.387), as shown in the Figure above. In this chart, there are around 80 materials within the selected area.

These are mainly carbon fibre reinforced thermosets and Beryllium alloys. At this stage, we realize that it is unrealistic to fully use the unidirectional (isotropic) properties of the fibre composites, because of the geometry of the heat shield and how it is manufactured. We therefore add a filter to screen out all unidirectional materials in a *Limit* stage, and settle for the woven, quasi-isotropic and biaxial lay-ups, etc. that give more realistic values of the lateral properties. This is done by unclicking the unidirectional option in the Composition overview for *Fiber/reinforcement form* (and possibly some other forms as well).

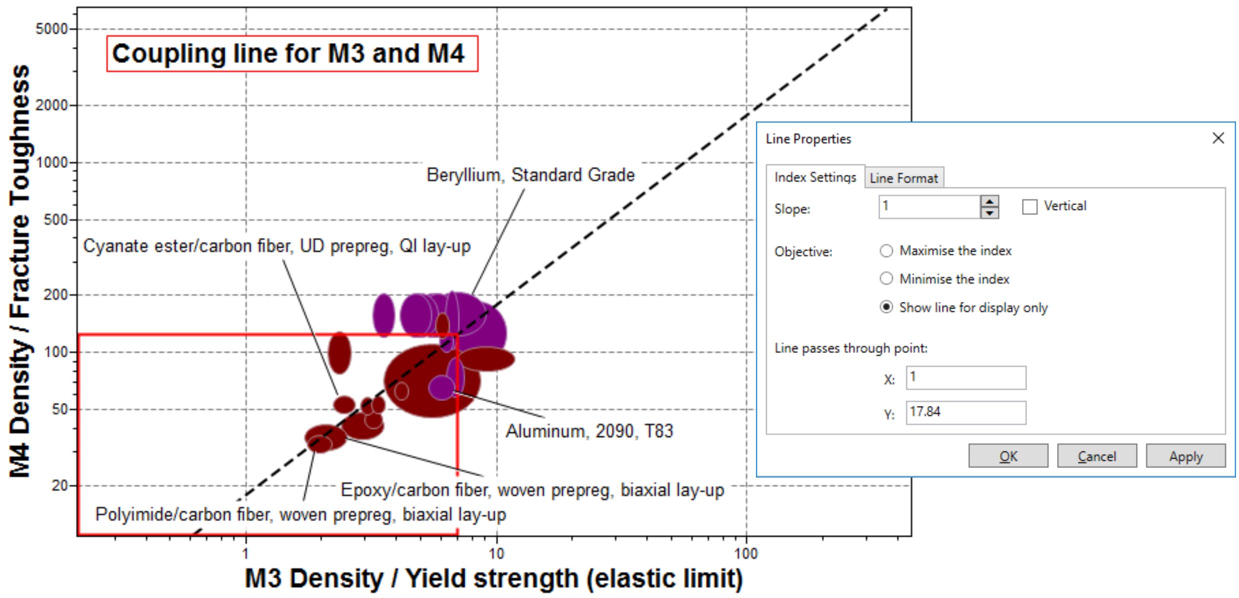


The second chart shows materials indices M3 and M4, with a coupling line. In the same way as for the previous chart, we create the coupling line, at which failure occurs at the same point for the two constraints reflected in M3 and M4. That is, where m_3=m_4 at the lower limits of the indices:

$$\left.\begin{aligned} m_3 &\ge \pi p R^3 (1-\cos\theta)\, M_3 \\ m_4 &\ge \pi^{3/2} p \sqrt{a_c}\, R^3 (1-\cos\theta)\, M_4 \end{aligned}\right\} \quad m_3 = m_4 \quad \Longrightarrow \quad M_4 = \underbrace{\frac{1}{\sqrt{\pi}\sqrt{a_c}}}_{C_c} M_3$$

Instead of two selection lines, we now use a selection box for the job, putting one corner on the coupling line. Again, the slope is 1 and the position of the line is determined by the coupling constant. The critical crack length to use depends on the size of defects that can be detected by testing. In this case, we will use a value of the critical crack length of a_c=0.001 m, resulting in a coupling constant of C_c=17.84.

The resulting materials are now determined by the two coupled charts and the candidates should perform well in both of these. Ideally, their masses should also match. In this case, we simply reduce the combined number of materials that pass the second selection to around 25, which includes Beryllium in the results.

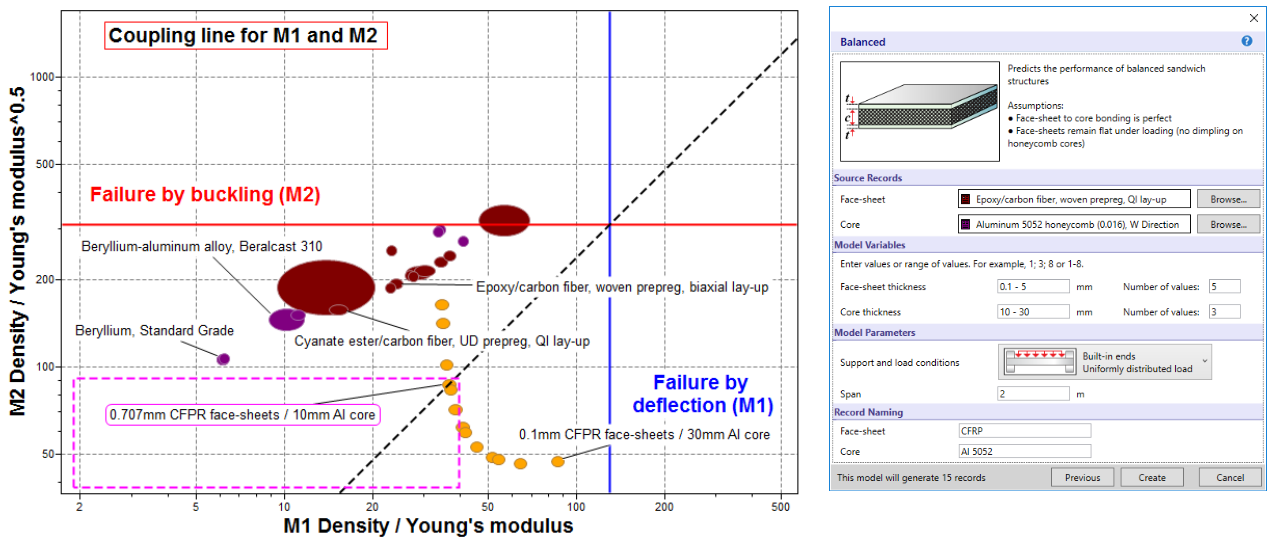


5. Analysis and reality check

The resulting materials are suggestions that should be scrutinized and discussed further. Are the parameters that we have used realistic? How can the coupling between the two charts be tackled? What about the sandwich panels used for the heat shield in the real Mars landers?

The optimal coupling between the two charts is something that could be elaborated, but which lies outside of the scope of this short case study paper. We can, however, use *the Synthesizer tool* with the *Sandwich panel model* to estimate and compare properties of the suggested materials with an Aluminum honeycomb core structure inside CFPR skins.

Data records were generated using the Synthesizer tool for a combination of materials available in EduPack: Epoxy/Carbon fiber composite and Al 5052 honeycomb. A distributed load on a panel with fixed ends and 2 m span was used as the closest approximation to the spherical cap of the heat shield.



The estimated results for a range of sandwich panels are plotted together with the remaining materials, revisiting the first chart, as can be seen above. The materials from the aerospace database are all located to the left of the coupling line, indicating that they would fail by buckling if the mass is reduced. The properties of the sandwich panels (in orange) are, indeed, better than the aerospace candidates. The best one in this case is indicated using the pink display box. It is clear from this example that the best performance is found in materials near to the coupling line, which represents a good compromise between the material indices. Sandwich panels of the type used in real Mars landers can be designed in this way and it is generally found that this hybrid structure is well suited for lightweighting in demanding applications.

6. What did CES EduPack contribute?

The Mars lander selection case study [6] provides an engaging platform for discussion of material selection in the field of Aerospace applications. In this case, we have explored how multiple constraints can be tackled with coupling lines, using basic equations and visual methods.

CES EduPack, combined with an educator's materials expertise, suggests the following conclusions:

- Since the main objective is to minimize mass, CES EduPack can help propose a number of aerospace materials that pass the mechanical and thermal constraints, for example: Carbon Fibre Reinforced Epoxy, Beryllium and Aluminum alloys.
- Two coupled charts could be used to select, based on material indices. The indices representing the four mechanical constraints were paired, where each pair could be related by a coupling line in the chart. The coupling lines are useful to match constraints in so called min-max problems.
- The Synthesizer tool of CES EduPack can generate estimated properties of hybrid structures being used in the actual Mars landers: Al honeycomb sandwiched between CFRP skins. These can be directly compared to the previous selection chart.
- The case study highlights the lightweighting benefits of sandwich panels, which is particularly important in aerospace applications.

References

1. General information on the Schiaparelli: https://en.wikipedia.org/wiki/Schiaparelli_EDM_lander
2. Design information: http://spaceflight101.com/exomars/schiaparelli-edm
3. Nasa's Thermal Protection Systems: https://www.nasa.gov/centers/ames/research/msl_heatshield.html
4. Roark's formulas for stress and strain, W. C. Young and R. G. Budynas (2002), 7th ed. McGraw-Hill
5. For example, see Ashby, M.F. (2016) "Materials Selection in Mechanical Design", 5th ed., Butterworth Heinemann.
6. Other case studies can be found here: http://teachingresources.grantadesign.com/Type/casestudies