Structural optimization as a design and styling tool
- with emphasis on truss structures...

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Introduction

This article presents an attempt to validate the use of structural criteria in a design/styling process. It is obviously seen from the point of view of a mechanical engineer with little knowledge of the paradigms of the design arts, and none of the formal schooling. As such, it should be seen more as a contribution to the general discussion of values in the field of "integrated design".
This project is done in the framework of the Danish Centre of Integrated Design, CID.

Stylist, designer, engineer...

Marcus Vitruvius Pollio (1st century B.C.), roman architect and military engineer in the time of emperors Gajus Julius Caesar and Augustus, devised the Vitruvian trinity of Firmitas (strength, stiffness, durability), Utilitas (use, function) and Venustas (form, beauty, aesthetics), as the key to design.

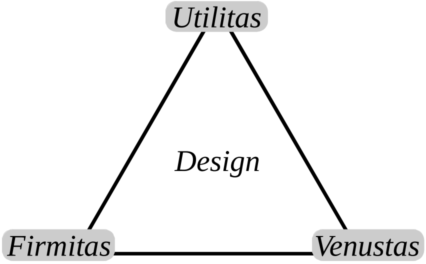

Fig. 1*: Vitruvius' triangle of design values/considerations*

It is rather difficult to imagine artefacts which do not, in some measure, relate to any or all of these three characteristics. However utilitarian a machine may be, we can have an opinion about its aesthetical qualities (if only by concluding that it is very ugly indeed) and about its strength. Even art in its purest form may be said to function by triggering some mental processes in the audience.
So, since most objects relate to all the three characteristics, the presence of these in any given artefact is hardly a measure of quality in the design process. Rather, it is relevant to see if some deliberate thought has been given to the process of integration. We may talk of the appropriateness of the applied characteristics in relation to each other.
Nevertheless, a common approach for people charged with creating an object is to focus on one characteristic alone, often disqualifying the other two in the process.
The two cases outlined below have been chosen as examples of the predictability when form and function are considered incompatible.
For confirming our prejudices, we may compare loudspeakers from two companies: Bowers & Wilkins (B&W) and Bang & Olufsen (B&O). Bowers and Wilkins have traditionally made

loudspeakers for the believing audiophiles, while Bang and Olufsen make products with a discrete but distinct visual profile. Clearly, the acoustician or engineer has the final word in the first case, while the designer (or stylist, as the case may be) decides in the second case. Again, speaking from our prejudices, the results are quite predictable.

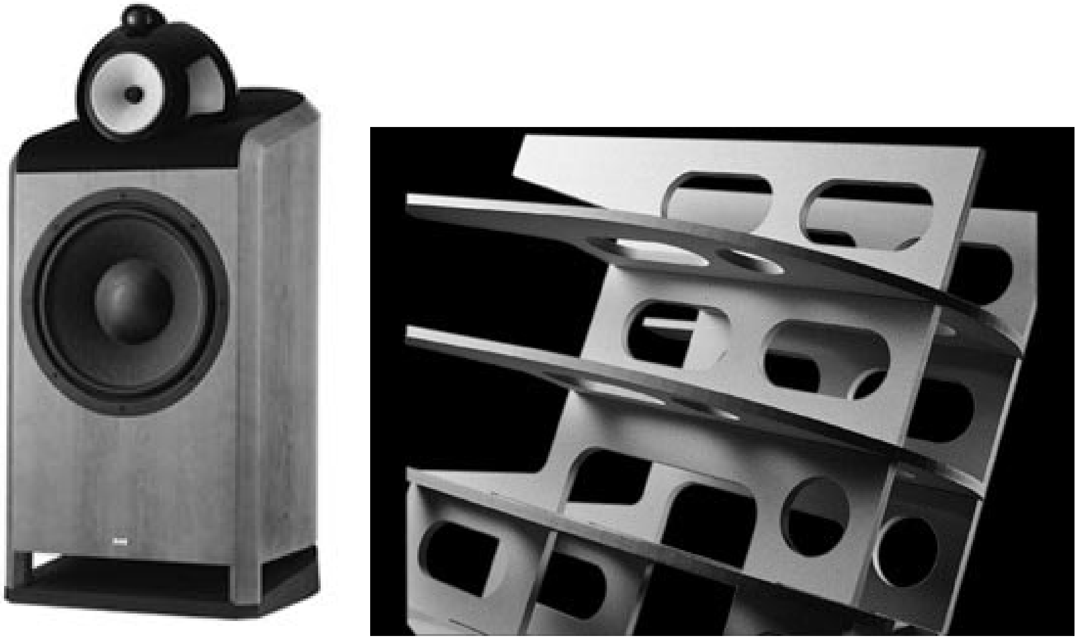

Fig. 2*: B&W Nautilus 801: This loudspeaker is a technically ambitious project, without compromises dictated by styling.*

Figure 2 shows a top-of-the-line loudspeaker from B&W. To the left is the whole loudspeaker, with three individual cabinets or chambers, one for each of the drivers (bass, midrange and treble). The shape of each chamber is optimized to avoid or control acoustic reflection; note for example the rounded back side of the bass chamber. To the right is a picture of the inner “matrix”-reinforcement of the bass chamber.

The acoustic precision is excellent, according to the reviews in different Hi-Fi magazines, and the craftsmanship is similarly superb. However, being the size of a small refrigerator, these loudspeakers are probably challenging to fit into an average living room...

***Fig. 3**: B&O loudspeakers, TV and stereo*

The design strategy at B&O consists of letting the designer/stylist define the exterior of the product, whereupon the technical problems may be solved[*]. The loudspeakers are slender with a small volume, which makes bass-reproduction particularly difficult. This calls for rather novel technical solutions. The “minimalist style” determines the design, and many functions are typically contained in a product with an unassuming exterior.

Acquired beauty

An important concept when discussing aesthetic qualities in relation to functional objects may be called “acquired beauty” as opposed to inherent beauty (which is a rather hopeless concept...). The B&W-speaker shown in figure 2 has been praised for its looks, but mostly by Hi-Fi enthusiasts. Its comeliness is probably more a function of association with the acoustic qualities.

A more extreme case may be seen in steam railway engines. These are the focus of a curious fascination. They are big, noisy, hissing, thumping, smoking, fire-breathing things (rather like a fairy-tale dragon), as far from any “classical” concepts of beauty as imaginable, and in stark contrast to the desirable qualities in a modern train (which are frankly boring in comparison). The steam engine is unashamed; it flaunts its elaborate mechanical linkages, pipes, safety valves etc. It bound large countries together, brought goods and news and people from one end to another. Again, any perceived beauty is defined by associated values; it is not “classical beauty”which is interesting, it is the ability to tickle our curiosity and sentiments. We cannot avoid having an opinion about the aesthetic qualities, whatever it may be.

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[*] "Ask Bang & Olufsen's principal designer, David Lewis, what his dream is and he will tell you that it's to create the first truly invisible loudspeaker. It may never happen, but by aiming for the impossible, we've already come a long way in producing a range of loudspeakers that are unique in their ability to combine the purest of sounds with the simplest of forms.

By the laws of physics, loudspeakers must take up space, but we choose to shape them so their physical presence is less intrusive and colour them so they compliment the surroundings in which they're placed. " Quote from B&O´s website.

***Fig. 4**: Classical heavy railway steam engine*

The visible drivetrain is doubtless a matter of maintenance - with everything easily accessible, the frequent repairs were less time consuming. Furthermore, people could directly see that the fire had been tamed and the “dragon” steered by the rails (the notion of a train continuing past the rails holds a certain dread; this has been used in several movies). Presumably, the fascination of taming nature´s forces is a very elementary emotion.
In the later days of steam engines, some efforts were made to improve the aerodynamic profile with a smooth exterior metal skin. One example, the “Mallard”, briefly reached a top speed of 125 mph (about 200 km/h) pulling six passenger cars between Glasgow and London. This was accomplished in 1938, on July 3rd. However, the frontal area of steam engines is rather small compared to the length, and the effect of diminishing the frontal drag probably quite small. Visually, it was no longer a “real” steam engine, the effect being rather like putting a chrome layer on a stone axe. As with many other technologies, the steam engine reached its pinnacle of development at a time when it was becoming obsolete.

Defining an optimum

It is occasionally said, by people working from a structural approach, that optimized structures are inherently beautiful. This reasoning gives further justification to increased efforts in that field (and is therefore not a bad thing), but it may be a simplification. It does not address the question of why. Optimization is, in its pure form, a tool for specialization and the art of extremes (exactly *this* widget for exactly *this* application), whereas the concept of aesthetics is more difficult to pinpoint. A formula 1 car may be considered beautiful because it is the right car for competing in the formula 1 series - placed on a gravel road it becomes, at best, an abstract (and rather expensive) piece of art; for the gravel road, we need something more versatile which, by definition, is more difficult to optimize. In this sense, a blind approach to aesthetics by optimization is futile. But optimization is a strong tool for adapting generic components to fit a particular situation. Used in this way, it may help not only in the aesthetic augmentation of a whole product, but actually in defining the aesthetics of the whole.

An optimal structure, in its pure form, is one in which all redundancy has been removed (the necessity, the whole necessity, and nothing but the necessity...). For determining what´s necessary, precise conditions must be defined, e.g. loads and available materials. Since there is no redundancy, a small change in geometry, materials or load outside the defined boundaries will either cause failure or cause the structure to be non-optimal. This sort of sensitivity may be observed, not just in the case of structures, but in several cases where optimization is applied, such as overspecialized animals, production facilities, and political ideologies, to name just a few.

It is clear that structural optimization can be taken to extremes only insofar as the parameters involved are well known. For practical purposes, the engineer always includes a factor of safety (or, more precisely, a factor of ignorance) to account for the unknown. This of course means including the necessary redundancy in the initial optimization formulation, and the structure becomes optimal within the probable limits of load.

The efficiency of a hole - implications of topology optimization

Over the last decade or so, computer programs for optimizing structural members have become commercially available (as add-ons for finite element programs). The most common type is shape optimization, where the initial geometric boundaries may change shape; this is a “tried and tested” approach. However, the initially chosen number of boundaries may not include the true optimum, hence the interest in topology optimization.

Topology optimization deals with the distribution of material within any set of boundaries, i.e. the number of holes in a structural member becomes a design variable. The process will typically result in a truss- or trellis-like structure. Figure 5 shows the progress of a combined topology- and shape-optimization in a, by now, classical example published by Olhoff, Bendsøe and Rasmussen /7/.

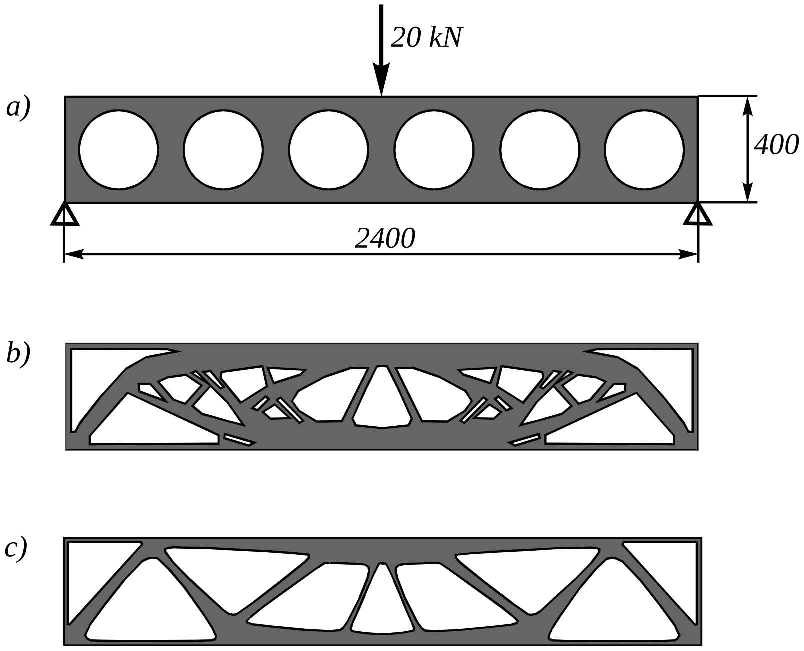

Fig. 5*: Improving the efficiency of a beam by a combined optimization.*
a) Initial geometry and load
b) Approximate geometry suggested by topology optimization
c) Final geometry, weight saving of approximately 40%

It is worth noting that the topology-optimization was used primarily in defining a feasible truss. This was then followed by a manual “clean-up”, and finally, the shape-optimization procedure was used for refining. Clearly, the trusses are worth a further study. The following example outlines the differences in efficiency between simple beams with one perimeter, and simple trusses with one outer and one inner perimeter.

Consider a load, placed at a distance of 1 meter from terra firma, here in the form of a vertical wall. For this calculation example, a vertical load of magnitude P = 1000 N will be used. Five plane cases will be considered:

a beam with a square cross-section,
a prismatic beam with width 10 mm,
a shape-optimized beam with width 10 mm, and
two trusses.

Material data will be as for a mild steel, and an (arbitrary) maximum stress of 100 N/mm^2 is allowed. Compression members in trusses are furthermore calculated as classical Euler columns, with tubular cross-sections and inner radius = 0.8 x outer radius. For each case, the necessary resultant mass will be calculated. The results are given in figure 6.

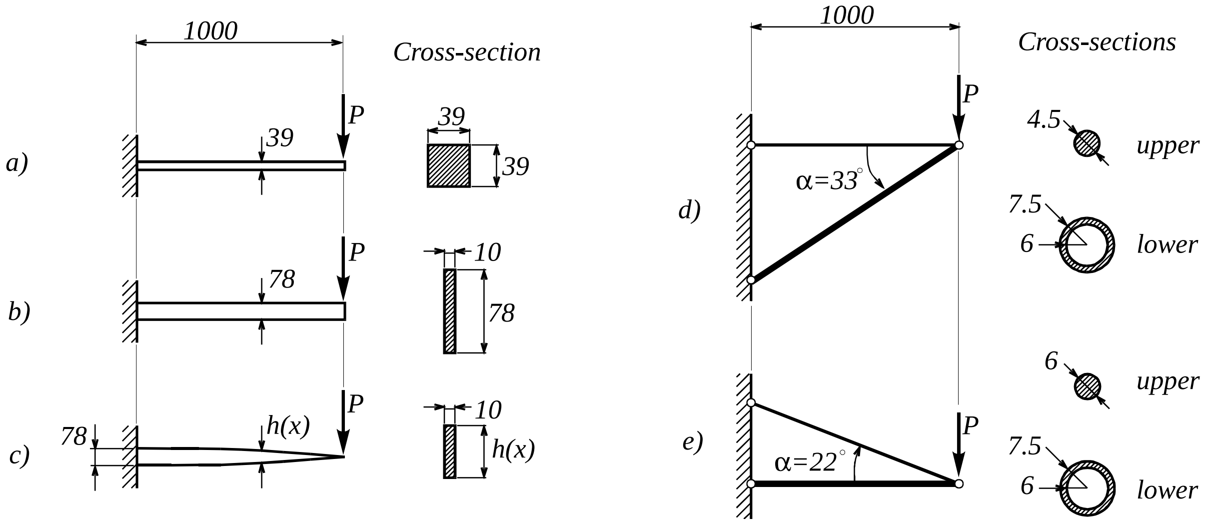

Fig. 6*: Beams (a, b, c) and trusses (d, e) designed for carrying the load P = 1000 N. Compression members in trusses are shown in thick line, tension members in thin line. The masses found are:*
*a) 12 kg b) 6.1 kg c) 4.1 kg d) 0.67 kg e) 0.67 kg**
**: Note that case e) is chosen as the configuration where the resultant mass is as for case d). The minimum mass for case e) is at* $\alpha = 62°$*, with a weight of 0.39 kg.*

Case a) is very elementary, though not infeasibly so. The structure is intuitively reasonable; we would trust it to hold a man weighing 100 kg. In case b), the material is placed further from the longitudinal centroid of the beam, making the structure more efficient for supporting the bending load. Case c) is designed for a constant maximum stress = 100 MPa in any transverse cross-section. We note that cases b) and c) are likely to be laterally unstable.
The relative weight reduction from case a) to case c) is approximately 2/3.

Cases d) and e) illustrates the difference between setting the tension or compression member at horizontal.

It is noteworthy that the mass may be reduced by a factor of almost 20 by choosing a truss structure over the least efficient beam design, and a factor of 6 compared to most efficient simple beam design. There is, of course, a price to be paid; the trusses take up more space, and loads may only be applied in the nodes (the vertexes where two non-parallel members are joined).

Michell´s truss

Things may be taken even further. Around the year 1900, A. G. M. Michell /1/ studied optimal structures, one example of which was for carrying a load much like the one discussed just above. He set restrictions on the truss-span at the fixture points, but allowed it to “balloon” at the midsection. The individual truss members would follow force trajectories, and cross each other at right angles[*] . Michell´s idealized trusses are impractical for most applications, but may be simplified to yield a feasible structure. This is shown in figure 7.

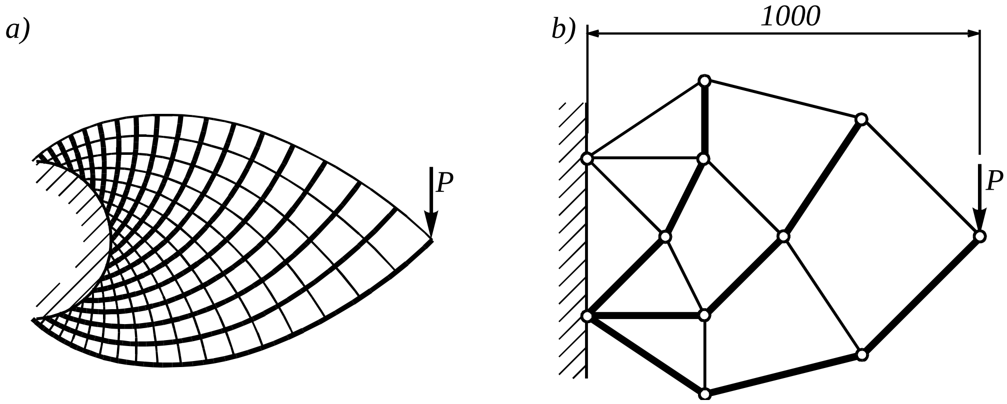

Fig. 7: *a) Michell structure (approximate rendition)*
b) Similar truss structure, simplified

The truss structure in fig. 7b) will, when calculated according to the same criteria as the previously mentioned trusses, reach a weight of 0.44 kg; the ideal Michell truss will be lighter still.

So much for the structural optimization, but what may be said about the aesthetic qualities? Certainly the Michell-truss is less boring than the simpler beams and trusses shown in figure 6. The complexity is confusing at first glance; this awakens the curiosity. A closer look at the structure reveals the logic.

The key word here may be “interesting”, rather than “beautiful”.

A peculiarity of the Michell truss is that most of the individual “cells” have four edges, as opposed to the normal three. A regular truss with four-edge cells will collapse, but the curved force trajectories of the Michell truss, in conjunction with the three-edge cells near the fixture points, makes the structure rigid like any other true truss structure.

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[*] : In fact, Michell idealized the truss to be composed of infinitely many infinitesimal elements; in effect a material which was at any point homogenous and orthotropic.

Michell´s definition was rather broader than outlined above. He considered a plane containing any set of curves which would cross at right angles. This includes couples of equiangular spirals (where the tangent is at all points at a fixed angle to the radius line) and circles in conjunction with radius lines. Circles and radius lines may be considered extreme cases of the equiangular spiral. Figure 8 shows some examples. It is interesting to note that one of them looks like a common bicycle wheel.

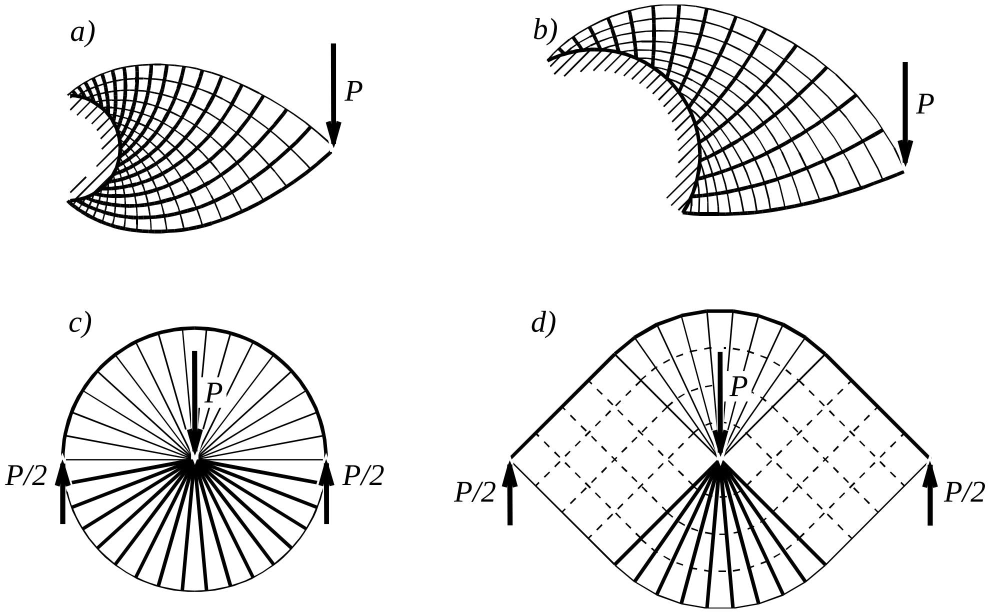

Fig. 8*: Different Michell-trusses. Tension members are shown in thin line, compression members in thick line.*

- *a) Equiangular spirals, both with 45° angle between radius and tangent*
- *b) Equiangular spirals, angles 27° (compression members) and 63° (tension members) between radii and tangents*
- *c) Circular-radial truss*
- *d) Circular-radial truss with rectangular-grid extension; dotted lines are in principle included but may be omitted as they transfer no load.*

The original paper by Michell is commendably short and to the point. In “The Design of Structures of Least Weight” /6/, Cox gives a fuller account of Michell´s ideas.

The mechanical structure of vertebrates is to some extent composed of very elaborate trusses, where the muscles are tension members and the skeletal bones are the compression members. In the book “Structures” /4/, J. E. Gordon elaborates on this, and applies considerations from Cox´s book to the distribution of muscles and bones. It appears that nature has abandoned the idea of producing structures with open holes on a macroscopic level; instead our skin forms a smooth surface. There are probably good reasons for this, such as diminishing the external surface area, although the “open truss” approach may be the most efficient from a mechanical point of view. Another reason is the limits for muscular contraction - a truss-structure would require a much larger ratio of contraction to uncontracted length than is possible with a normal muscle.

On the microscopic level, holes are abundant, as may be seen from sections of leaves, branches, bones and much more. Indeed, both the equiangular-spiral and the circular-radial Michell-structures are readily seen in a section through a thighbone.

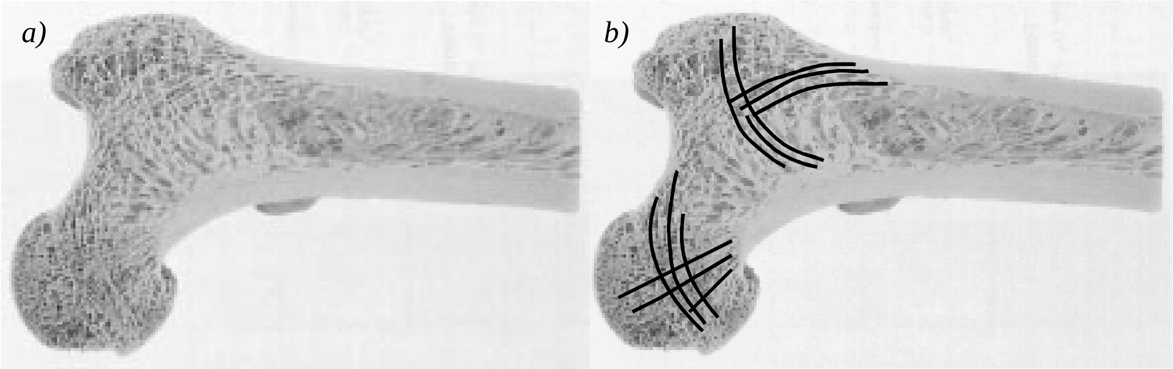

Fig. 9*: Section through a human thighbone. The Michell-structure is shown enhanced on the right.*

According to Gibson and Ashby /5/, studies indicate that the growth (material distribution) of the cancellous* bone develops to follow the force trajectories.

In the study of biomechanics, the exact interaction of muscles and tendons in a joint can be quite complicated. Muscles may act counter to the principal direction of movement, acting as a stabilizing force. In that case, the force trajectories in the bone can strongly hint at the general force transfer direction in the joint.

Trusses as a design element

Michell´s structures are feasible only in extreme cases, although approximate versions are quite effective, as demonstrated above. For most applications, a normal trellis made from welded steel pipes gives very good results, apart from the economical advantages of low-tech production requirements. Unfortunately, trellis structures are often designed without considering the aesthetic impact; this tendency classifies them as the technocrats “low-budget” options to something better. Belgian cartoonist Franquin /3/ portrayed a construction site as the nightly battleground of skeletal monsters, as the trellis cranes came alive; this was probably a profound insight into our subconscious perception.

The disregard for the visual impression is a great pity, since the trellis structures have a good potential in terms of interesting and exciting design; they don´t have to be straight box-sections. Masts for high-voltage power cables are a case in point, and it is rather surprising that people accept the scare-crow monstrosities that litter the landscape. Figure 10 shows a typical example of a trellis mast.

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* : “Cancellous” means that the bone tissue has a relative density less than 70% of the density of solid bone.

***Fig. 10**: Trellis mast for high-voltage cables.*

A bit of aesthetic consideration in the design would make a great difference. The extra expenses would be minimal, in light of the sheer amount of such masts. Fortunately, newer types show a bit more promise...

***Fig. 11**: A different style of masts for high-voltage power cables*

In the automotive industry, trellis-frames (or truss-frames) were used to a great extent in earlier days. Early airplanes had fabric covered truss-wings and fuselages. With biplanes in particular, the two parallel wing surfaces connected by struts and wires gave a box-section truss of great rigidity.

Earlier examples include the eskimo kayaks; these are a particularly good example of choosing a structural layout from available materials (a limited amount of driftwood and a good deal of seal-skins). Cars are a peculiar and rather atypical example. The earliest cars were more or less direct copies of the structure of horse-drawn carriages, plus one motor and minus the horses. The frame of the car was structurally very simple, consisting of two longitudinal beams. This layout exists even today in lorries, for several reasons: The twin-beams with free cross-sectional deformation give a low torsional rigidity, allowing the load to distribute on all the wheels (the torsional flex of a lorry travelling over rough roads is easily visible), and the beams permit loads to be applied in any points. In that sense, truss structures have not been used very much for cars, and what examples there were have been replaced almost exclusively by plate-monocoques in the case of small cars. There is a certain structural logic in this: The car must have a smooth exterior in order to minimize aerodynamic drag, so plates are a necessity, and they might as well carry the primary load. Still, some low-volume producers use trellis frames since the price of plate-shaping tools is prohibitively high unless a very large number of cars are made, and some extreme cars are built around (or, rather, inside) a trellis frame, taking advantage of the stiffness. It also serves as a roll-cage in case of the car overturning; this is seen most clearly in rally-cars. The aerodynamics are then handled by covering the car with a lightweight body.

Motorcycle frames

As implied, any trellis or truss is associated with a structural purpose. The use of a truss in a given application indicates to the observer that some deliberate thought has been given to the transfer of loads; as opposed to this, the use of a beam may often seem less sophisticated (compare the beams and trusses in figures 5, 6 and 7). In short, a truss or trellis shows that the designer knows what he/she is doing. Trellis frames are a feasible choice for motorcycles, since the loads and force transfer points are comparatively well definable.

Motorcycles will be used as examples in the following, since they present an interesting case study. First of all, they mostly don´t constitute a rational mode of transportation; in town, the small, modern scooters are equally effective, and on longer journeys the average family car is often preferable in terms of transportation capacity and comfort. Moreover, the fuel economy of small cars is rapidly approaching that of medium-to-large motorcycles[*] . The greatest appeal by far of motorcycles is immaterial values which, among other things, means that the law of diminishing returns doesn´t apply. Practically every motorcycle has the same everyday utilitarian value (predictable handling and the ability to transport one or two persons at legal motorway speed or lower, which probably accounts for at least 90% of all motorcycle use), so the difference between a 1500$ motorcycle and a 15000$ motorcycle lies in the potential to venture into the realm defined by the last 10 percent. These are obviously the economically interesting 10%, which can justify the development of exotic components, such as elaborate frames.

One of the better examples of deliberate use of a trellis as a styling element is found in the Ducati motorcycle frames. The Ducati Monster, in particular, was instrumental in using and indeed defining this trend. The structural efficiency of the trellis itself has been discussed in the above, but

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[*] The situation may be changing towards a more favorable position for motorcycles. With increasing commuting from residential areas, most larger cities are getting congested with traffic. Motorcycling present a good way of combining medium-distance commuting with less demand for physical space.

in cultivating the minimalist approach defined by the trellis, an overall balance was reached, both in terms of aesthetics and structural performance.

***Fig. 12**: Ducati Monster. The trellis frame is exposed and utilized as a shape element in the overall design. Picture courtesy of Motorcycle Online Inc.*

In figure 12, the directions defined by the trellis members may be followed in the tank cut-out, the seat slope, the engine angle and the exhaust angle. The riders thighs will fit in the tank cut-out and extend the line given by the seat.

The Ducati Monster was designed by Miguel Angel Galuzzi, who, at the separation of Ducati from the Cagiva group, followed Cagiva Research Centre. His influence is easily seen in the Cagiva Raptor, see figure 13.

***Fig. 13**: Cagiva Raptor. The use of the trellis frame follows the same tendencies as in the Ducati Monster. Picture courtesy of Motorcycle Online Inc.*

Several japanese manufacturers have followed suit, although they tend to use cast aluminium for their trellis frames. With the use of modern aluminium casting methods, it is possible to make optimum shapes of the fillets between the members in the truss, thus minimizing the stress concentrations in these areas. This involves a basic shape optimization, as described earlier. A discussion of different motorcycle frames may be found in Gaetano Cocco´s “Motorcycle Design and Technology” /2/.
Massimo Tamburini, chief designer at CRC at the time when Galuzzi designed the Monster, now does design for MV Agusta. The MV Agusta Brutale is a “naked” version of the MV Agusta SP4 sports-/racebike, and the trellis frame is again an integral part of the design. The MV Agusta motor is an inline four-cylinder, as opposed to the V-2 motor used in the Ducati and the Cagiva. An inline four with the crankshaft transverse to the motorcycle length-axis is rather wide, and the trellis frame curves around the top of the motor (a so-called perimeter frame). This combines to produce a dense, muscular visual impression.

Fig. 14*: MV Agusta Brutale. Picture courtesy of Motorcycle Online Inc.*

Massimo Tamburini has expressed some very definite views on the approach to motorcycle design. In an interview with AMASuperbike.com, he said: “When the designer doesn't have a good understanding of the mechanical side of things, he can never design a good product.”[*] . It should be noted that Tamburini is, without comparison, the most celebrated motorcycle designer today. The Ducati 916, for example, is his design.

Transparency - or Form follows Function

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[*] Tamburini continues: “Only an engineer can create a good product in the first instance, and then be assisted by a good designer”. Philippe Starck tried his hand at motorcycle design, with the Aprilia Moto 6.5. This goes some way towards demonstrating Tamburini´s point, harsh though it may seem.

Continuing the example of motorcycles, and with the risk of oversimplifying, one might say that motorcyclists have a liking for transparency, in the sense that the purpose of things should be apparent from the visual expression; there is a certain honesty of purpose. The motorcycle is rather elementary, as is the act of motorcycling: It involves only that which is necessary. In the process of minimizing and optimizing, each component will stand out and state its purpose. The fuel tank is bulbous, clearly defining a volume for fuel, and we expect it to be so. Suspensions at front and rear are mostly commendably simple, consisting of telescopes and swingarm. The frame, in whichever form it takes, provides fixture points for all other components and must therefore provide (and give the impression of) stiffness and strength. This is all part of the transparency. The designer has displayed his skills rather than hidden his flaws.

Final remarks

The work of designers is often made difficult by a lack of quantifiable goals, particularly in the styling processes. This article was intended to whet the designers appetite for adapting a structural, functionalistic approach.

The focus has been mainly on trusses as structural elements. The trusses, by their very nature, makes statements about force directions and magnitudes; a clever designer will know how to make good use of that information. But it will be suitable to take, as a final example of applied structural optimization, the design of a beam. Santiago Calatrava designed the Stadelhofen railway station in Zürich, Switzerland. Figure 15 shows the platform roof. The inclined cantilever beams carrying the roof itself is easily analyzed:

***Fig. 15**: Platform roof at Bahnhof Stadelhofen, Zürich.*

One of the primary loads on the roof is the weight of snow in the winter, i.e. an evenly distributed load q (figure 16a). For constant maximum stress along the cantilever beam of width w, the shape becomes triangular (figure 16b). Some modification for production and connection with the carrying tube gives the final shape (figure 16c).

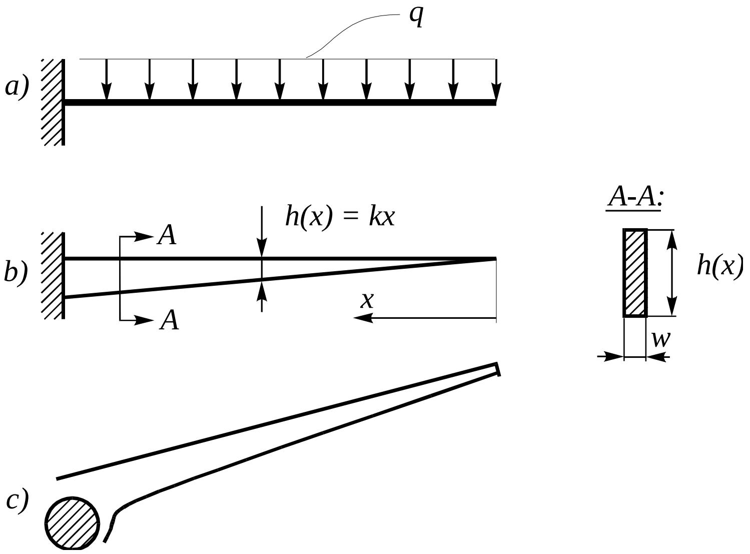

Fig. 16: *Design of cantilever beam for carrying an evenly distributed load.*

a) *Distributed load q.*
b) *Optimum shape for constant stress, width w*
c) *Modified shape*

Even the column, standing vertically from the concrete foundation to the roof mounting (figure 15), is shape-optimized, bulging at the middle and thin at the ends.

Returning briefly to Vitruvius, it has been demonstrated that the difficultly definable quality Venustas can be adressed by considering Firmitas.

Structural criteria have the advantage of being clear, well-defined, and quantifiable. A structural optimization of a crucial component, using a sufficient number of design variables, often produces interesting results (which can be used as guidelines in the remaining design). In this way, an optimized component still leaves room for interpretation and augmentation. At the very least, it tells the end-user that the product has received the attention of the designer; it was not an indifferent product and, by way of the product, the designer has given attention to the user.

An indifferent product is an insult.

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