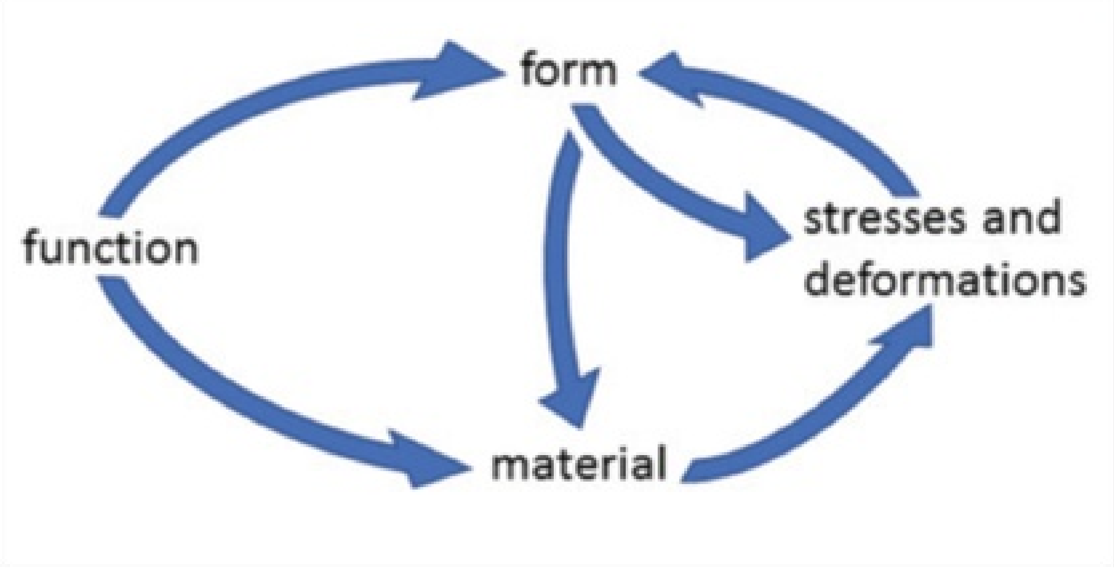
Materials design for tunnel linings

In this article, Dr Benoit Jones of Inbye Engineering looks at materials design for tunnel linings.

THE MANTRA OF THE MODERNIST MOVEMENT of the early 20th Century was "form follows function". In contrast, Ashby & Johnson (2014) argue that often, form is not particularly limited by the function. A steel structure is likely to be rectilinear, a concrete shell structure is likely to be domed, a masonry structure will be made of discrete blocks, will be arched or will have limited spans. In civil engineering, as in product design and mechanical engineering, we tend to choose our materials first, then design a structure. In many cases it is not so much that "form follows function", but rather that "form follows material".

The concept of 'materials design' as pioneered by Professor Mike Ashby is to turn this on its head. The designer thinks about the desired form and features and searches for the best material to achieve them. This is not a linear process, and there is interaction between the choice of material, the loads and the form (Figure 1). However, the difference between this process and the usual one is that the designer keeps an open mind about the material selection.

Figure 1: Conceptualisation of the design process



Form and features of a tunnel

The form and features of a tunnel will depend to some degree on its function. However, apart from requiring a minimum cross-sectional area (for a water or sewage conveyance tunnel) or a minimum space envelope (for pedestrian or traffic tunnels), the form is not usually restricted such that it drives the design. It is quite common, for instance, to design highway tunnels as circular, or consisting of one or more circular arcs, when the space envelope is often closer to a rectangular shape. Therefore, "form follows material" seems to be the case for most tunnels, not "form follows function".

Apart from the ability to withstand stresses and control deformations to acceptable levels, features that are usually considered are (e.g. ITA, 1988):

- Watertightness
- Durability
- Fire resistance
- Not harmful to people or to whatever is transported by the tunnel, and non-toxic to the ground and groundwater
- Minimise carbon footprint
- Buildability

The first 4 in the list above are pretty much yes/no answers, where materials can be ruled in or out. It is not quite that simple, since aspects such as watertightness, durability and fire resistance could be provided by combining more than one material, as we currently sometimes do when combining concrete with sheet membrane waterproofing. Also, durability may depend on crack widths, which depend on structural response.

Assessing the equivalent CO_2 emissions of a material to provide its carbon footprint is not difficult nowadays, though assessing the relative importance of this compared to other factors, such as cost, requires some assumptions.

Structural demands

The relationships between strength and weight density or between modulus of elasticity and weight density are critical to the design of materials for many types of products and structures, and have driven the development of modern metal alloys, fibre composites, technical ceramics, polymers and sandwich panels, that are lightweight, strong, stiff and resilient (Ashby & Johnson, 2014). However, self-weight of a tunnel lining is not an important consideration in and of itself. Making a tunnel lining lighter will only be beneficial if it reduces cost, either by reducing volume of material used, or by reducing the volume of excavation. In a shaft or tunnel design, sometimes weight is a good thing as it counteracts uplift pressures.

So what is important to a tunnel lining? It needs to withstand compression, but also shear and bending. It needs to have a minimum stiffness to control deformations, but flexural stiffness has a knock-on effect of increasing the bending moments when ground stresses are uneven or when the shape of the tunnel is non-circular. In order to make some broad generalisations, first we need to simplify.

Kuesel (1987) argues that axial stiffness of a tunnel lining is what allows redistribution of stresses in the ground, but flexural stiffness should be as low as possible. For example, if the ground deforms the lining elliptically, Kuesel says that it is the axial stiffness that transfers the stresses and allows an equilibrium to be achieved. The flexural stiffness does little to restrain ground deformations and only serves to increase bending moments in the lining. As long as there are no voids behind the tunnel lining, Kuesel says a lining cannot fail in flexure independent of ground deformation.

Browsing the literature for moment-axial force ('M-N') interaction diagrams gives a sense of typical loads in a tunnel lining. Usually these published values are for ground and water loads and may ignore construction loads such as jacking loads from a TBM, which may be more critical. They also rarely show a lining that fails, because they are usually describing successful design. The majority of these plot in the lower half of the M-N diagram, as illustrated in Figure 2, where *h* is the thickness of the lining, *b* is 1m length of

Figure 2: M-N interaction diagram showing typical zone of concrete tunnel lining designs

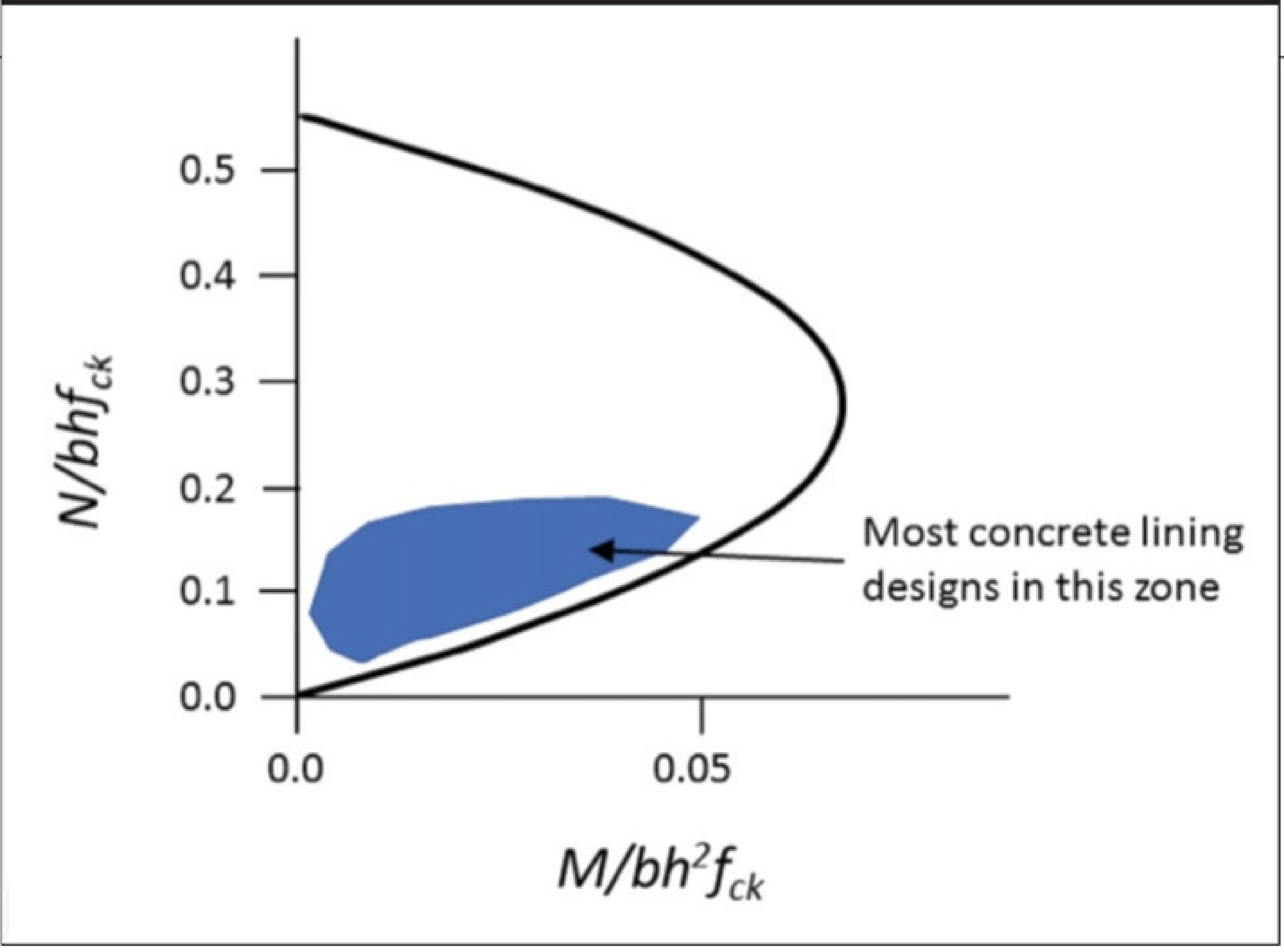
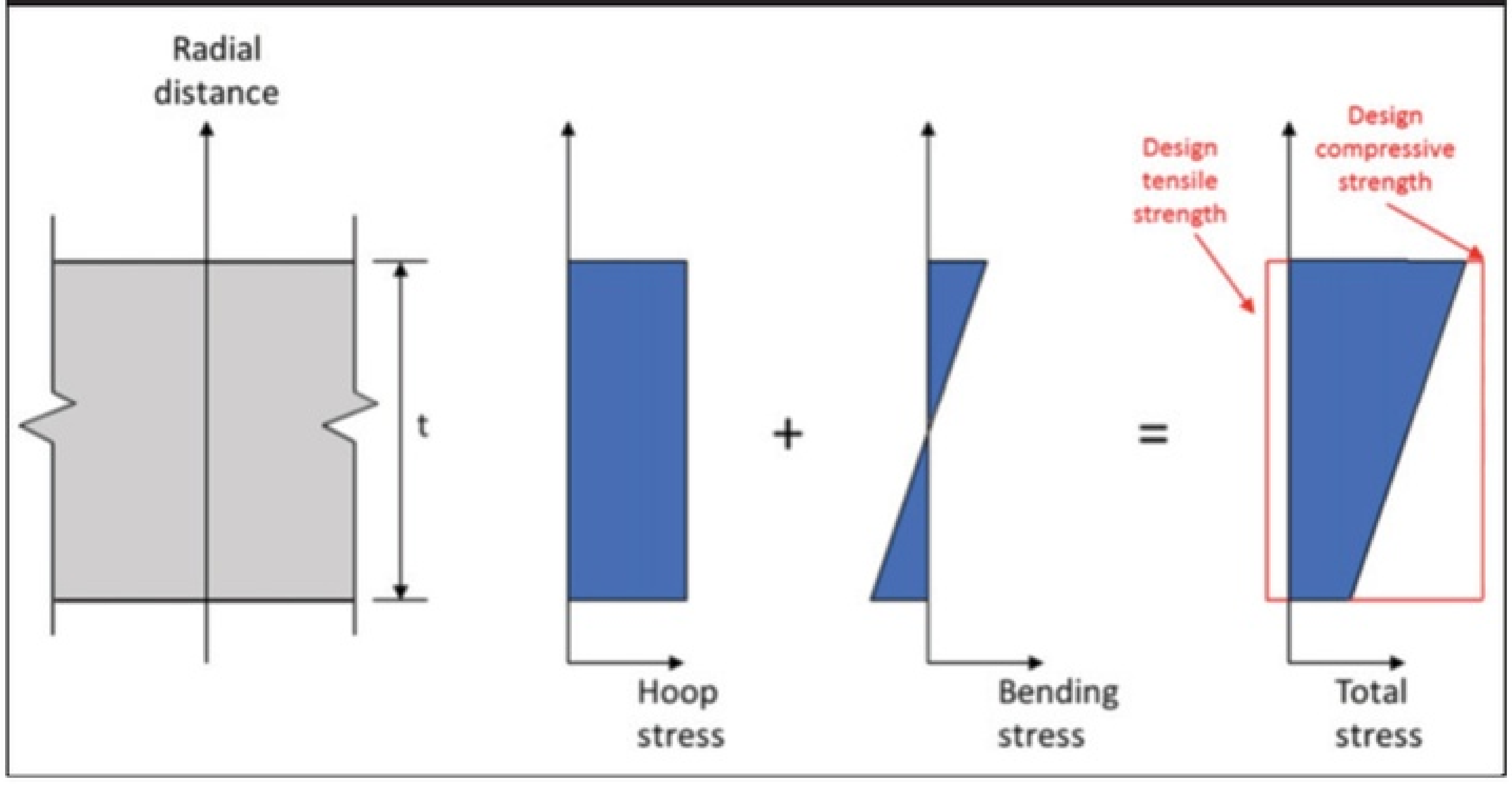


Figure 3: Stress distribution across the thickness of a tunnel lining



tunnel, f_{ck} is the characteristic cylinder strength of the concrete. *N* is the axial (hoop) force and *M* is the bending moment. The curve shown on Figure 2 is the capacity of the section, in this case plain concrete with no reinforcement, to withstand a combination of *M* and *N*; as long as design values of *M* and *N* plot inside it, the ultimate limit state is ok.

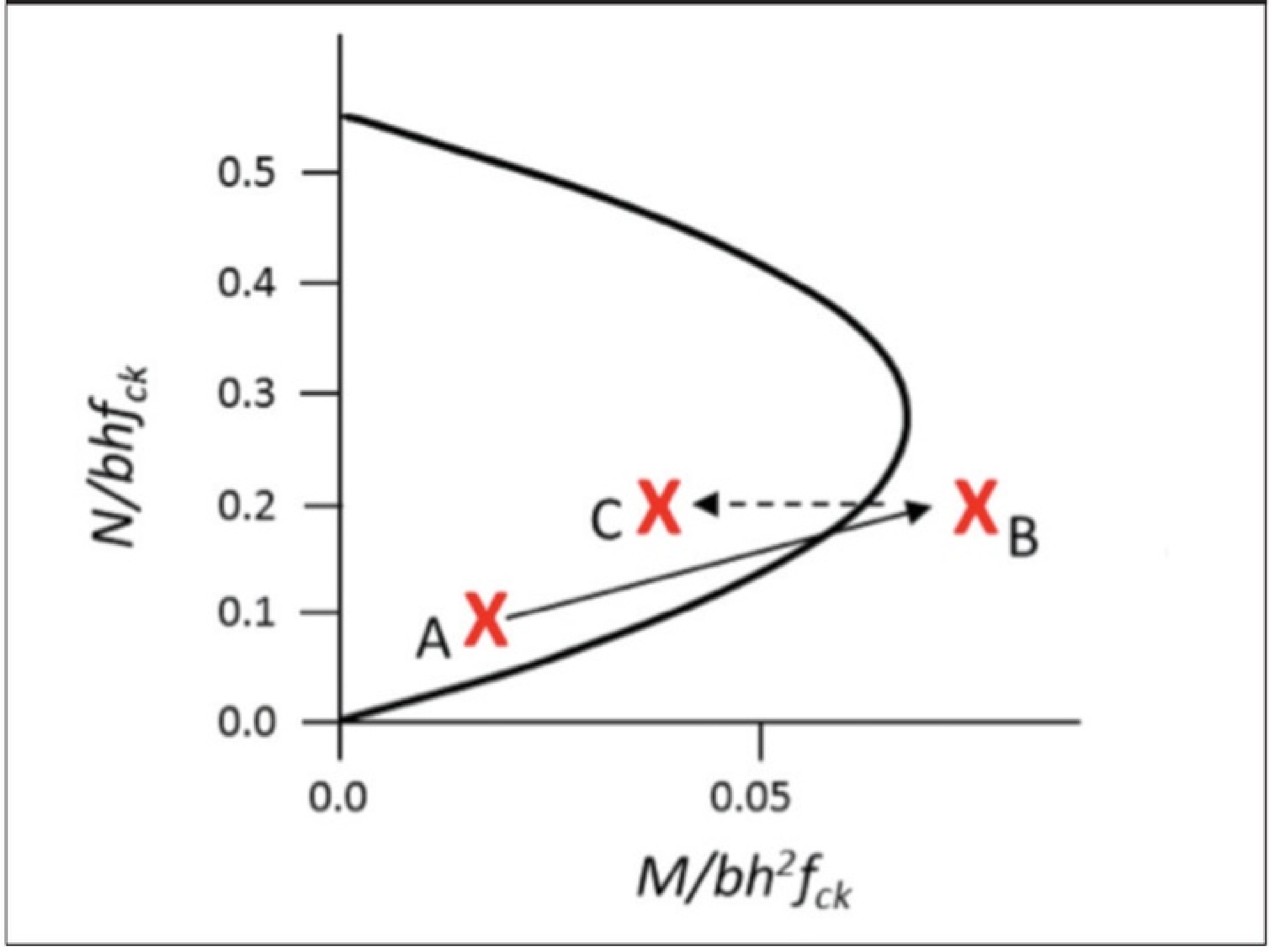
Figure 2 shows that when we are in the bottom half of the capacity curve, higher hoop forces are beneficial, in that they allow a larger moment to coexist. This is because concrete is weaker in tension than in compression, and when the hoop and bending stresses across the section are added together, as shown in Figure 3, neither the design tensile strength nor the design compressive strength can be exceeded. For the more advanced readers, note that Figure 3 assumes linear elastic stress-strain behaviour to make things easier to understand, whereas the capacity curve in Figure 2 assumes a nonlinear stress-strain relationship as recommended in BS EN 1992-1-1: 2004 (hence why it is curved and not two straight lines).

Ignoring soil-structure interaction, if a slimmer lining were used and ***h*** were divided by 2, this would move a point in the interaction diagram upwards as N/bhf_{ck} would increase by a factor of 2. However, M/bh^2f_{ck} would at the same time increase by a factor of 4, moving the interaction from point A to point B in Figure 4, effectively because we have reduced the moment capacity of the section. However, knowing what we know about soil-structure interaction, as h is reduced, the moment of inertia *I* of the lining reduces dramatically as it is proportional to $h^3/12$, and we should expect *M* to reduce significantly, perhaps to a point C.

In the other direction, designers often find they are chasing their tails. When the lining has insufficient moment capacity one option is to increase the reinforcement, but this is often undesirable if the designer is trying to design with plain concrete or a particular dosage of fibre reinforcement, and trying to avoid the need for steel bar or mesh reinforcement. So instead they increase the thickness of the section to increase its moment capacity. The soil-structure interaction analysis is then run again, but unfortunately the new, thicker lining has higher bending moments, so the lining needs to be made thicker still.

A reasonable conclusion from this discussion is that if unreinforced or lightly reinforced concrete linings are desirable, improvements could be made to reduce their flexural stiffness and thus reduce their thickness. Historically, this has been achieved by having radial joints in

Figure 4: Effect of reducing lining thickness by a factor of 2



segmental linings that are designed to articulate. In recent years, there has been a trend towards using fewer segments with stiffer joints that are almost always staggered in the longitudinal direction, further increasing the flexural stiffness of the ring.

An alternative solution would be to use a different material. Clearly a material with a better tensile strength will work better as a thin lining that is flexible but has axial stiffness. This has led to research into new materials for tunnel linings, such as engineered cementitious composites (ECC) by Morgan Sindall UnPS with the University of Surrey (Boughanem, 2014), and this will be discussed in the following section.

It is often the case that segment design is driven by construction loads, in particular the jacking forces, and not the ground and water loads in the permanent situation. If linings really are significantly thicker because of this, then perhaps we need to think about the way jacking forces are transferred to the tunnel lining to reduce material consumption, cost and CO_2 emissions.

New concrete tunnel lining materials

Engineered cementitious composite (ECC)

Sometimes called ‘bendable concrete’, ECC can sustain tensile strains of 3-7% (Said et al., 2015). It is a cementitious mortar containing small short polymer fibres, usually poly vinyl alcohol fibres 8-10mm long and 38 microns diameter. The fibres encourage growth of a large number of microcracks with a specific width of less than 50 microns. The first crack appears at quite a low tensile stress of about 2.5MPa and the ultimate tensile strength will be around 4.6MPa. Therefore, a thin ECC lining would not only provide a low flexural stiffness with a good axial stiffness, but it also provides high levels of ductility. The small crack widths also allow autogenous self-healing.

High performance fibre-reinforced cementitious composites (HPFRCC)

HPFRCC contains polymer or metal fibres and exhibits strain hardening when loaded beyond its initial peak. ECC is a special subset of HPFRCC. The steel fibre reinforced concrete used for the Lee Tunnel lining (Hover et al., 2015) was a kind of HPFRCC, as it exhibited strain hardening behaviour after first crack.

High strength-high ductility concrete (HSHDC)

ECC and HPFRCC have excellent properties, and the increased ductility will enable larger deformations and distortions without failure, and the smaller crack widths will improve durability. But what we really want is a higher tensile strength. HSHDC has a high compressive strength > 150MPa, high ductility with an ultimate strain 3.7-4.8%, and relatively high tensile strength at 14.5MPa (Ranade et al., 2013).

All these cementitious composite materials could work as thin tunnel linings. Their main drawback is the high cement content (ECC has more than 800kg/m^3, HSHDC has approximately 900kg/m^3), which will increase cost and increase the carbon footprint per m^3 relative to ordinary concrete. However, if significantly less volume is needed, these materials may be a better option.

Other materials

There may be other materials that could be used instead of cementitious materials. ‘Ashby charts’ (Ashby & Johnson, 2014) are a fantastic tool for finding materials with the material properties you are looking for. In the range of tensile strengths from 10-100MPa, there are mostly metals and metal alloys. Assuming that these are probably too expensive, the other materials in this zone are polymers such as polyethylene, polypropylene and PTFE, and glass fibre reinforced polymers.

It may seem that there are plenty of reasons why some of these materials may not work, but perhaps we should think about how the construction and installation method could be adapted to make them work and we may end up with a better tunnel.

Conclusions

We have looked briefly at a ‘materials design’ approach to tunnel linings, and it has potential to bring new insights on what materials may be suitable for tunnel linings. A more detailed examination may be worthwhile.

Fibre reinforced cementitious materials have the potential to be as ductile or more ductile than conventional reinforced concrete, and can have much higher compressive and tensile strength. If this can lead to thinner linings, the higher cost per unit volume may be justified.

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LETTER TO THE EDITOR

I congratulate TJ and Prof Arnold Dix in publishing a very stimulating article on the outcome of the Glendoe case and one which I hope will be widely read by tunnelling clients and contractors. There is one point on which I’d like to comment. There is reference under the heading “Mistrust grows” to HSE providing “advice on a mediation strategy”. I believe this should read “advice on a remediation strategy”. HSE never sought in any way to influence the relationship between SSE and Hochtief or to express a preference for the remedial works contractor. My comments to SSE at the meeting of 12th October, related to the provision of a concrete invert in the headrace tunnel and the determination of the size of the void and its propagation upwards (Paragraph 122 of Lord Woolman’s “Opinion”).

Yours faithfully

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HSE, 1989 – 2010.