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Elastic Strain Energy Release at Failure and its Consequence for Structural Glass Testing and Design

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The amount of elastic strain energy that is being released upon initial failure of a structural glass element has profound influence on its post-initial failure load bearing capacity. This paper discusses the relevance of this notion to the evaluation of structural glass testing and the consequences it may have for structural glass design. It means, among others, that post-failure behaviour may be highly geometry dependent as well as strongly related to the cause of the initial failure (as both determine the amount of energy released at failure). The options to limit the consequences of energy release will be discussed. The result of application of one of these options to the design of reinforced glass beams is shown.

Keywords: Elastic Strain Energy, Failure Behaviour, Testing, Design.

1. Introduction

It has been shown the amount of elastic strain energy released upon initial failure of a structural glass element influences its post-initial failure load bearing capacity. More specifically, [1] came to this conclusion:

The *external* elastic strain energy release at the moment of initial failure of a glass element, influences the maximum post-failure resistance, in a way that a release of more energy generally results in less post-failure resistance, either by premature failure of the tensile component as a cause of the shock load or through the extent of crack growth/branching. The following points should be noted:

- The importance of the extent of crack growth reduces with increasing tensile stiffness of the 2nd Load Transfer Mechanism (LTM; i.e. the mechanism activated after initial failure, e.g. when linear elastic bending of the glass section is superseded by a composite action of glass in compression and a laminate material in tension). The fracture pattern density may become irrelevant with high stiffness elements, such as steel reinforced glass beams.
- The differences in crack growth between annealed, heat strengthened, and thermally tempered glass, as a result of internal (i.e. from thermal prestress) elastic strain energy release, govern over those caused by external (i.e. caused by loading) elastic strain energy release.
- When the release of internal elastic strain energy is sufficient to disintegrate the glass, this may effectively distribute the shock load over the tensile element,

thus avoiding direct rupture and improving post-failure resistance (over a condition in which the tensile element ruptures).

These conclusions were drawn based on several observations reported in literature [2], [3], [4], as well as extensive experimental research

- on 14 glass beam designs tested for post-failure resistance after having sustained different levels of predamage (none, partial, or full),
- and on reinforced glass beams with different section properties and hence different energy absorption at failure.

The tests on glass beams with different levels of predamage, clearly showed the post-failure resistance reduced when the energy release at initial failure was higher (i.e. when the level of predamage was low), see Figure 1. The relation is particularly visible with the 2.PVB.A (double layer, PVB-laminated, annealed glass), 3.PVB.A, 3.SGP.A designs, which show a gradual increase of post-failure resistance with decreasing energy release at failure. In these designs, the post-failure resistance is governed by glass crack pattern density (high energy release causes a more dense pattern, resulting in less compressive capacity and thus less post-failure resistance; figures 2a, b, c). Not immediately obvious, but also energy related is the post-failure resistance in the 2.PVB.S (heat strenghthened) and 3.PVB.S beams. In this case, the crack pattern density is not governing, but rupture of the PVB interlayer that occurred in all but the fully predamaged beams (figure 3). This, too, is a phenomenon related to elastic strain energy release. A high energy release causes a shock load on the tensile element, in this case resulting in PVB rupture.

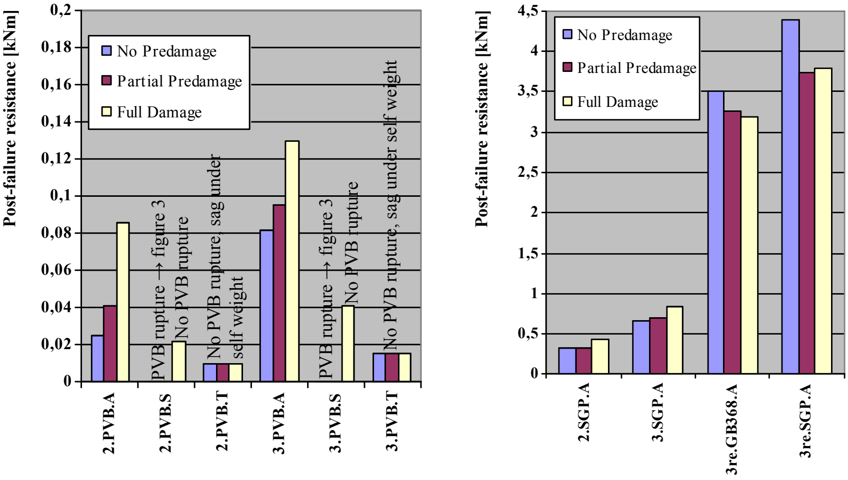


Figure 1: Dependency of maximum post-failure resistance of different glass beam designs on the level of predamage applied. No predamage causes high energy release, full damage causes low energy release.

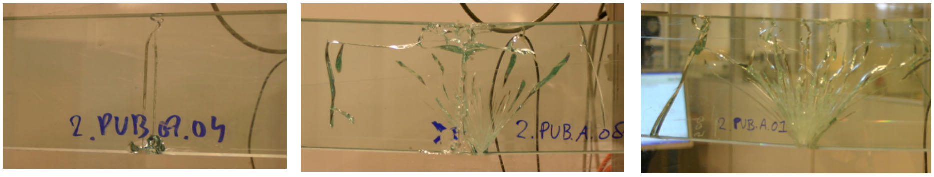


Figure 2a, b, c: Fracture pattern at initial failure in a double layer annealed glass beam tested in 4-point bending after respectively: both glass layers broken by predamage (full damage), 1 layer broken by predamage (partial damage), no predamage.

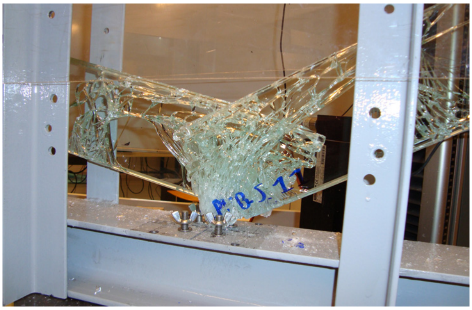


Figure 3: Collapse occurs immediately at initial failure in double layer PVB laminated heat strengthened glass beams tested in 4-point bending after no or partial predamage (this picture: no predamage), because of tearing of the PVB foil.

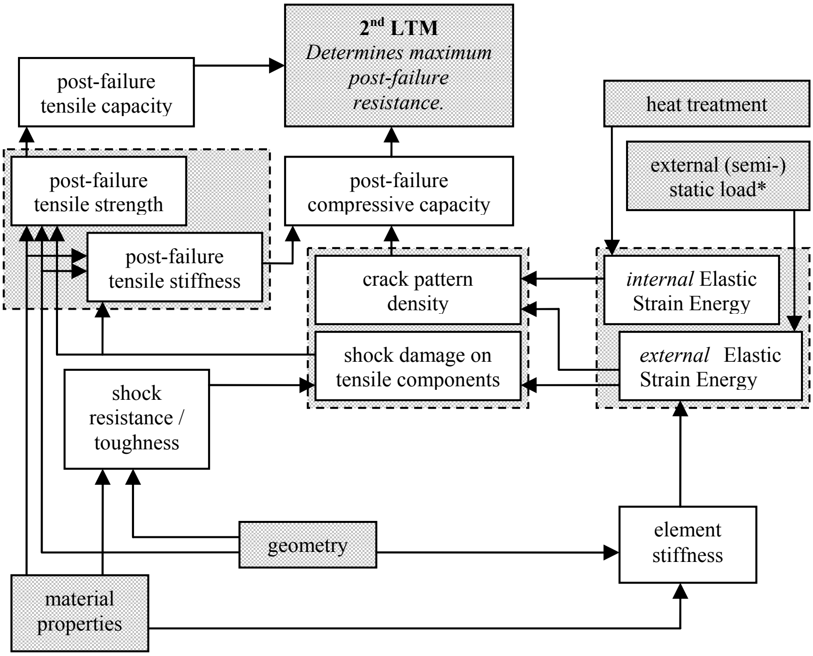


Figure 4: Schematic summary parameters influencing the maximum post-failure resistance of the 2nd LTM.

The other test series gave the important addition that the influence of elastic strain energy release reduces with higher post-failure stiffness. It also became clear the energy release is just one of many factors influencing post-failure resistance, see Figure 4. These issues have been discussed more extensively in [1], as well as in [5].

2. Relevance

The relation between elastic strain energy release and post-failure resistance, obviously, is relevant because post-failure resistance is a crucial property of structural glass elements to obtain safety.

The post-failure resistance of an structural glass element may be described by its secondary Load Transfer Mechanism (2nd LTM; its primary one being the mechanism describing its resistance before failure, e.g. linear elastic bending of a beam).

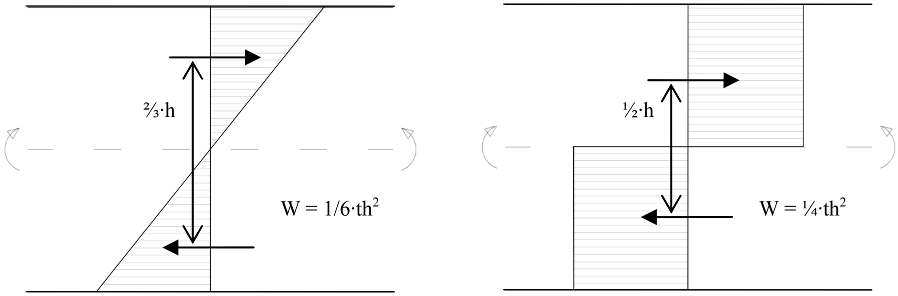
A 2nd LTM is usually presented as a static analytical mechanics model or calculated from (semi-)static FE models [4], [6], based on the application of a stress-based failure criterion together with stiffness reductions to predict crack growth (rather than include dynamic (energy-driven) crack growth modelling). In spite of the role of elastic strain energy release on the post-failure resistance as indicated in Figure 2, its influence is never incorporated in the analytical or FE modelling of 2nd LTMs. However, by looking again at the experimental results on the 14 glass beam designs mentioned above, it will be shown the release of external and internal elastic strain energy may actually determine what 2nd LTM develops.

2.1. Elastic Strain Energy Release and The Effective 2nd LTM

In laminated glass beams, the laminate must carry the tensile loads after failure. In some cases the cracking pattern is too dense or the laminate is not stiff enough to allow compressive stresses in the (broken) glass, and the interlayer thus remains the only active material. In others, the laminate works in composite action: the glass in compression and the interlayer in tension. Four 2nd LTMs are proposed, Figures 4a – d. Ranked according to capacity, they are:

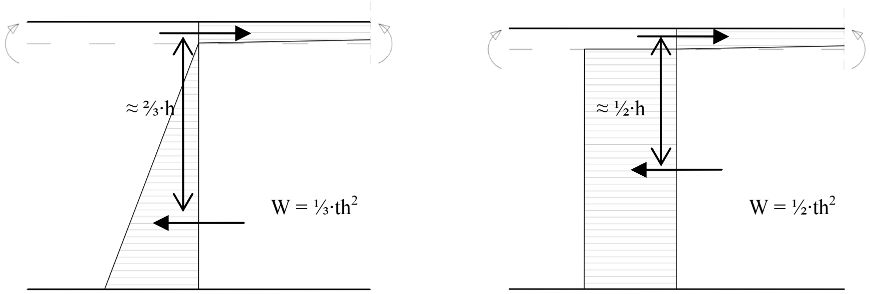
- 1: linear elastic bending of just the laminate,
- 2: plastic bending of just the laminate,
- 3: composite action with laminate in elastic bending and glass in compression,
- and 4: composite action with laminate in plastic bending and glass in compression.

The theoretical capacity of each 2nd LTM was calculated, and, based on the experimental results, it was determined which one is applicable to each beam design and level of pre-test damage. The results are listed in Table 1. This clearly shows the elastic strain energy release affects the 2nd LTM that develops after initial failure, and thus relates directly to one of the most important safety parameters of a glass element. Additionally, it is important to realize that the post-failure resistance of an element can thus not be established without specifically indicating the impact type (and thus the energy release) with which failure is to be obtained.



2nd LTM 1

2nd LTM 2



2nd LTM 3

2nd LTM 4

Figures 4a – d: Four alternative 2nd LTMs that may develop in a double or triple layer laminated glass beams.

Table 1: 2nd Load Transfer Mechanism per specimen type, per predamage level – sorted by beam type. A '0' means there is no 2nd LTM is present.

2nd LTM			
Specimen Type	Predamage level		
	none	partial	full
	corresponding energy release at initial failure		
	high	**medium**	**low/zero**
2.PVB.A	0 – 1	1	3
2.PVB.S	0	0	0 – 1
2.PVB.T	0 – 1	0 – 1	0 – 1
3.PVB.A	1	1	3
3.PVB.S	0	0	0 – 1
3.PVB.T	0 – 1	0 – 1	0 – 1
2.SG.A	3 – 4	3 – 4	4
3.SG.A	3 – 4	3 – 4	4

2.2. Consequences of the Elastic Strain Energy Release Parameter

Because of its crucial influence on the 2nd LTM in a glass element, the elastic strain energy release at initial failure in a glass element is critical to the question of how to obtain safety. This has consequences for the appreciation of existing methods to calculate post-failure resistance as well as the interpretation of experimental results and the development of glass elements with safe failure behaviour.

First, it should be concluded that the existing FE-models as mentioned above, should be fundamentally questioned as methods to predict crack growth. Agreements with observations made in experiments may be (partially) accidental. Although valuable insights in the distribution of stresses in the post-failure state of elements is provided, they do not constitute a predictive method with which failure behaviour can be determined and post-failure resistance predicted. They can, therefore, only be indicative tools to design and determine the dimensions of glass elements. Much more research is required in this field so that predictive models for failure behaviour and post-failure resistance can be developed.

Furthermore, the geometry dependency of elastic strain energy raises a number of issues that should be considered regarding the further development of safe glass elements:

- Negative scaling effects can be expected when increasing the size of (innovative) elements, as e.g. proposed by [7]. Because of the stiffness of the tensile component, increased crack pattern density is not so much likely to become a problem. However, the shock load on the tensile system, particularly on the glass-to-steel adhesive, may induce collapse at initial failure or premature final failure. When alternative brittle reinforcement materials are used, such as CFRP profiles, this could also cause premature collapse.
- Test results on smaller size specimens can not be safely extrapolated to larger sizes without further consideration. Full-scale testing should be preferred, especially when tensile components with relatively low stiffness are applied.
- Although PVB rupture at initial failure was only witnessed in directly tested heat strengthened glass beams, it could also occur:
    - In larger size annealed glass beams.
    - In larger size heat strengthened beams which do not fail by overloading, but by e.g. a combination of static and impact load.
    - In larger size SG-laminated beams.

3. Elastic Strain Energy and Structural Design

In order to avoid excessive energy release inducing premature failure or sub standard post-failure resistance, two strategies are basically available: minimize elastic strain energy content in structural elements, and counteract the effects of energy release – also see Figure 4.

3.1. Minimizing Elastic Strain Energy Content in Structural Elements

For elements behaving linear elastically to failure, the total strain energy content U_ε depends on the strain energy density χ distribution over the element body. The strain energy density, in turn, is the stress integrated over the strain at a point, which, for linear elastic materials, yields Eq. (1). The stress is obviously determined by the well known relations Eqs. (4) and (5), for bending and normal loads.

$$\chi = \tfrac{1}{2}\sigma\varepsilon = \tfrac{1}{2}\frac{\sigma^2}{E_{eff}} \tag{1}$$

$$\text{For bending: } \sigma = \frac{M}{W}\text{; For normal loads: } \sigma = \frac{S}{A} \qquad (4),(5)$$

From these equations, the strategies to limit strain energy content can be deducted:

- Increase the effective elastic modulus (E↑)
- Decrease the stress (σ↓), by:
    - Reducing the failure stress (σ_{max}↓),
    - Reducing the external moment (M↓),
    - Reducing the external load (S↓),
    - Increasing the section surface area or the moment of resistance (A↑; W↑)

Each of these strategies will be briefly discussed.

The effective modulus of elasticity can be increased by raising the glass Young's modulus through alteration of the composition. Options for this have been discussed in [1]. It is not likely transparent high Young's modulus glasses will be commercially available for application in building construction in the near future. Alternatively, therefore, complementary components (e.g. reinforcement profiles) with a high Young's modulus could be applied. Steel or CFRP may therefore be more effective as reinforcement than, for instance, aluminium. However, since the complementary components are generally only a small part of a glass element section, it is questionable whether this would significantly alter the E_{eff}. Furthermore, alterations in E_{eff} only linearly affect the elastic strain energy content. It is therefore more effective to consider stress reducing options.

There is a number of possibilities to reduce the stress at failure and thus the energy release. Perhaps trivial, but the first option is to reduce the failure stress of the material. The effect of this was shown by the difference in failure behaviour of directly tested 2.PVB.S and 2.PVB.A glass beams (Figure 1): while the former collapsed by PVB tearing at failure, the latter could still retain some resistance after initial failure. However, in practice this option will not be of much use, as it simultaneously means a reduction in load carrying capacity.

Reduction of the moment in an element, on the other hand, may be a more realistic option. There are several ways to achieve this. A possibility that should not be overlooked for bending governed elements, is altering the support conditions. The moment integrated over a beam length can be reduced by almost 2/3^{rds} when changing the system from freely supported to rigid connections on both sides.

The moment can also be reduced by limiting the span or the external load. This may be done by designing finer structures, e.g. with smaller centre distances (this may decrease the span of roof plates and reduce the load on roof beams).

Finally, the geometrical sections properties may be changed. For bending governed elements, the moment of resistance can be increased. This will automatically also increase the load carrying capacity (assuming the failure stress remains unchanged). To obtain an element with equal resistance but less energy content, the moment of inertia can be changed by adjusting the *t/h* ratio. This approach may be limited by stability considerations (e.g. lateral torsional buckling).

3.2. Reducing the Effects of Strain Energy Release on a Structural Element

Instead of minimizing the strain energy content at failure, the influence of the energy release may be reduced. Three strategies are available:

- Increase the shock absorption capacity of the complementary component – either its material fracture toughness or its geometry (e.g. laminate thickness).
- Increase the stiffness ($E_{eff}I$ or $E_{eff}A$) of the 2nd LTM.
- Distribute the energy release over a larger area of the complementary component. As discussed before, the sudden PVB-rupture in directly loaded heat strengthened beams did not occur in thermally tempered ones, despite their significantly higher failure load and energy. The reason was that the dense fracture pattern of thermally tempered glass distributes the shock load over a much larger portion of the laminate, than single crack origin which occurs in heat strengthened glass.

3.3. Application of Effect-Reducing Measure: SG-Laminated Reinforced Glass Beams

The strategy of reducing the effects of energy release was successfully applied in a further development of the reinforced glass beams developed at the TU Delft (e.g. [8]). Previously, they had all been bonded by GB368 UV-curing acrylate adhesive. Final failure has regularly been caused by failure of the adhesive layer which is damaged (debonded) around the initial crack origin and subsequently debonds outwards in the post-failure stage, until the remaining adhesive layer is insufficient to carry the loads and breaks, resulting in final failure. An improved beam design uses SG as a laminate and bonding material. With both a higher fracture toughness and layer thickness, this adhesive/interlayer system can absorb much more shock energy than the GB368 bond.

The SG bonded reinforced glass beams showed consistently higher levels of residual strength and displacement than those bonded with GB368. This should be attributed to the development of a different 2nd load transfer mechanism in the post-initial failure stage, made possible by a) the transverse crack stopping properties of the interlayer, and b) the elastic strain energy absorbance capacity of the interlayer.

The post-initial failure strength of the GB368 bonded specimens was governed by the moment capacity of one or two plastic hinges which occurred along the beam length (Figure 5). These plastic hinges consist of a compressive glass zone in the top and a tensile steel zone at the bottom. The capacity of these hinges can be determined by quite simple two-dimensional analytical calculations.

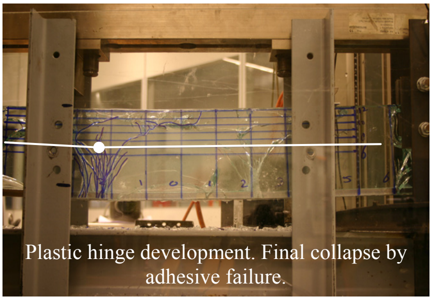


Figure 5: Plastic hinge determines 2nd LTM in GB368 bonded reinforced glass beams. Maximum theoretical capacity is 3.59 kNm.

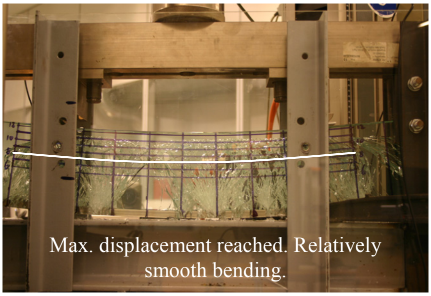


Figure 6: A more complex system involving overlapping glass segments and shear loads, determines the 2nd LTM in SG laminated reinforced glass beams.

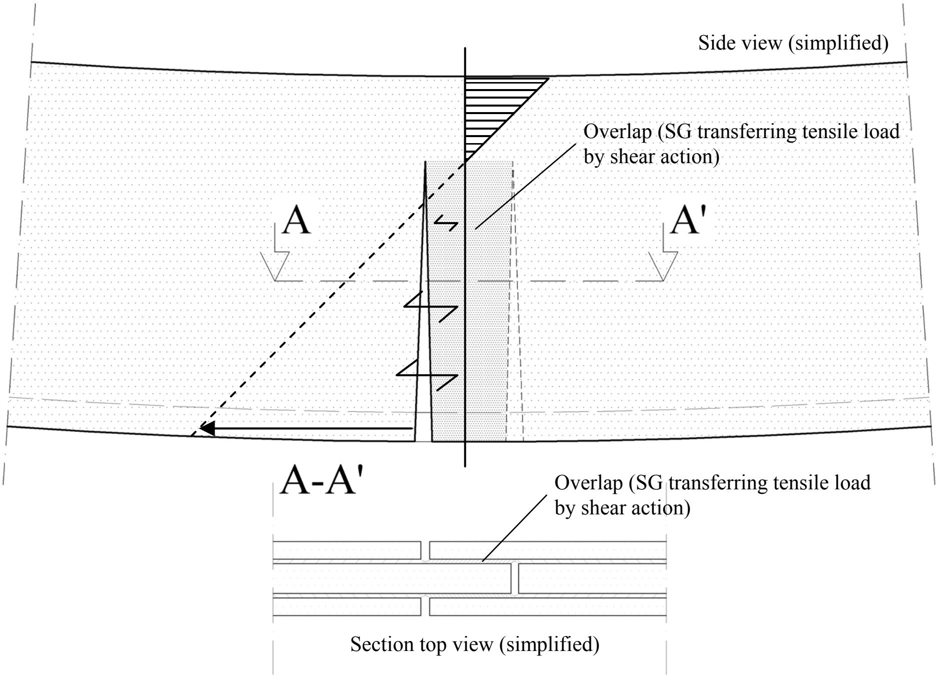


Figure 7: Simplified representation of the extra tensile capacity provided by shear loaded SG.

The SG bonded beams however, showed post-failure resistances well above what can be maximally obtained through this mechanism (namely $r_{res,III,ave}$ = 4.38 kNm, while $r_{res,III,max\ theoretically}$ = 3.59 kNm), Figure 6. This can be explained by the presence of an additional tensile capacity provided by overlapping glass segments transferring tensile actions through shear loaded glass-SG-glass bonds (Figure 7) – thus resulting in a different 2nd LTM.

For this mechanism to work, the non-coincidence of glass cracks in the various layers, is crucial. In transverse direction, this is ensured by the crack stopping properties of the SG laminate. In the longitudinal direction, the higher energy absorbance compared to GB368 plays a crucial role: less delamination results in shorter cracks and less concentration of cracks (Compare Figures 5 and 6). The natural variation of bending tensile strength along the edges of glass sheets also provides a 'natural' spread of crack origins.

So, the application of a more shock resistant adhesive layer improved the performance of the element in post-failure both on the tensile side (no adhesive failure) and compressive side (more favourable crack pattern development).

4. Conclusion

It was shown the post-failure resistance of structural glass elements depends on the amount of elastic strain energy released at initial failure. The energy release determines the secondary Load Transfer Mechanism that may develop after failure. As a consequence, particularly the geometry dependency of test results on structural glass prototypes should be recognized. There are two basic strategies to avoid premature failure because of too much energy being released: 1) to reduce the energy at initial failure, 2) to counteract its consequences. The latter strategy has been successfully applied in the further development of steel reinforced glass beams, by replacing the GB368 UV-curing acrylate adhesive with SG-laminate. This resulted in a different secondary Load Transfer Mechanism and therefore higher post-failure resistance.

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