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The Integrated Approach to Structural Glass Safety Applied to Glass Beams

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This paper presents a safety classification of 14 different of glass beam designs based on experimental research, using the Integrated Approach to Structural Glass Safety (introduced by the author, [1], [2]). The design parameters included the number of layers (2 or 3), the level of prestress (annealed, heat strengthened, thermally tempered), and laminate type (PVB or SG). Additionally, steel reinforced glass beams were tested. Three different methods were applied to obtain complete redundancy curves (development of residual strength under increasing levels of damage): 4-point bending after no, partial, or full damage. The damage was applied by a custom made impact device consisting of a spring loaded flat steel head that impacted the edges of the glass layers of the beams. The resulting Element Safety Diagrams of each design is discussed. Relativized curves are used to compare the safety of the designs.

Keywords: Glass beam, Failure Behaviour, Comparison, Damage, Redundancy

1. Introduction

In the previous publications, the author has introduced the Integrated Approach to Structural Glass Safety [1], [2]. This method to evaluate the safety of glass elements is based on the introduction of four element properties: damage sensitivity, relative resistance, redundancy, and fracture mode. The Element Safety Diagram (ESD) was presented as a tool to provide a quick and relatively complete overview of all relevant safety properties by combining them into one diagram. In this paper (based on [1; Chapter 7]), experimentally determined ESDs of 14 glass beam designs are presented. The ESD is evaluated as a tool.

The ESDs were obtained by applying three different test methods to each beam design:

- Method A: Direct displacement controlled 4-point bending (support span 1400 mm; load span 400 mm) test, at 2.0 mm/min until initial failure and subsequently at 5.0 mm/min, on as-delivered specimens.
- Method B: 4-point bending test as A on specimens, damaged according to Damage Method 1.
- Method C: 4-point bending test as A on specimens, damaged according to Damage Method 2.

Damage Method 1: Damage was applied by consecutive impact on the bottom edge of all layers (to create *model level III damage*, [1; Chapter 6], which equals initial failure).

A custom-designed spring loaded impact-device was used (Figure 1). The impact device was adjusted so that it created a crack over the entire height of the impacted sheet.

Damage Method 2: Damage was applied by consecutive impact on the bottom edge of a layer, while simultaneously being subjected to a static load. Of the double layer specimen, one layer was impacted (to create *model level I damage*); of triple layer specimens, both outer layers were impacted (to create *model level II damage*). The static load was in each case equal to the calculable strength of the remaining undamaged layers.

An overview of beam designs is presented in Table 1. All specimens were 1500 mm long. The tests resulted in preliminary ESDs as the one shown in Figure 2, in which the parts and elements are explained. The ESDs of each beam design presented in the subsequent section should be considered to be preliminary, basically because too few experimental results were available. As a result, the time dependency of resistance was omitted in the presented diagrams.

Table 1: Specimen overview.

Spec. Type	Section Geometry t_{gl} x h [mm]	Laminate / Bond	Heat Tr.
2.PVB.A	(2x10)x120	PVB	Ann.
2.PVB.S	(2x10)x120	PVB	Str.
2.PVB.T	(2x10)x120	PVB	Temp.
3.PVB.A	(3x10)x120	PVB	Ann.
3.PVB.S	(3x10)x120	PVB	Str.
3.PVB.T	(3x10)x120	PVB	Temp.
2.SG.A	(2x10)x120	SG	Ann.
2.SG.S	(2x10)x120	SG	Str.
2.SG.T	(2x10)x120	SG	Temp.
3.SG.A	(3x10)x120	SG	Ann.
3.SG.S	(3x10)x120	SG	Str.
3.SG.T	(3x10)x120	SG	Temp.
3re.GB368.A	(6-10-6)x125	GB368, reinf.	Ann.
3re.SGP.A	(6-10-6)x125	SG, reinf.	Ann.

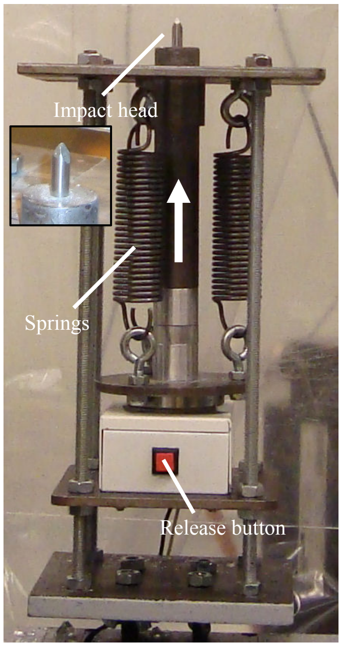

Figure 1: Impact device.

The required magnitudes for two types of impact are presented to obtain the model damage levels I, and, for the triple layer specimens, II. For the top model damage level (II or III, depending on the design), only one impact type is presented. Type *a* Impact (left vertical bars) is a spring loaded, concentrated hard body impact on a glass sheet edge. Alternatively, the same physical damage can be obtained by a combination of a static load and a spring loaded impact, indicated as Type *b* Impact. Clearly, much less impact energy is required when a static load is present to obtain similar physical damage.

It is important to note that the failure behaviour of glass beams is geometry dependent, as it is partially determined by the elastic strain energy content at failure [1; Chapter 9], [3]. Thus, the ESDs presented in this Chapter are valid only for the investigated geometry. Although they may present an indication of the failure behaviour of differently sized beams, they may not be assumed to be generally valid for any geometry.

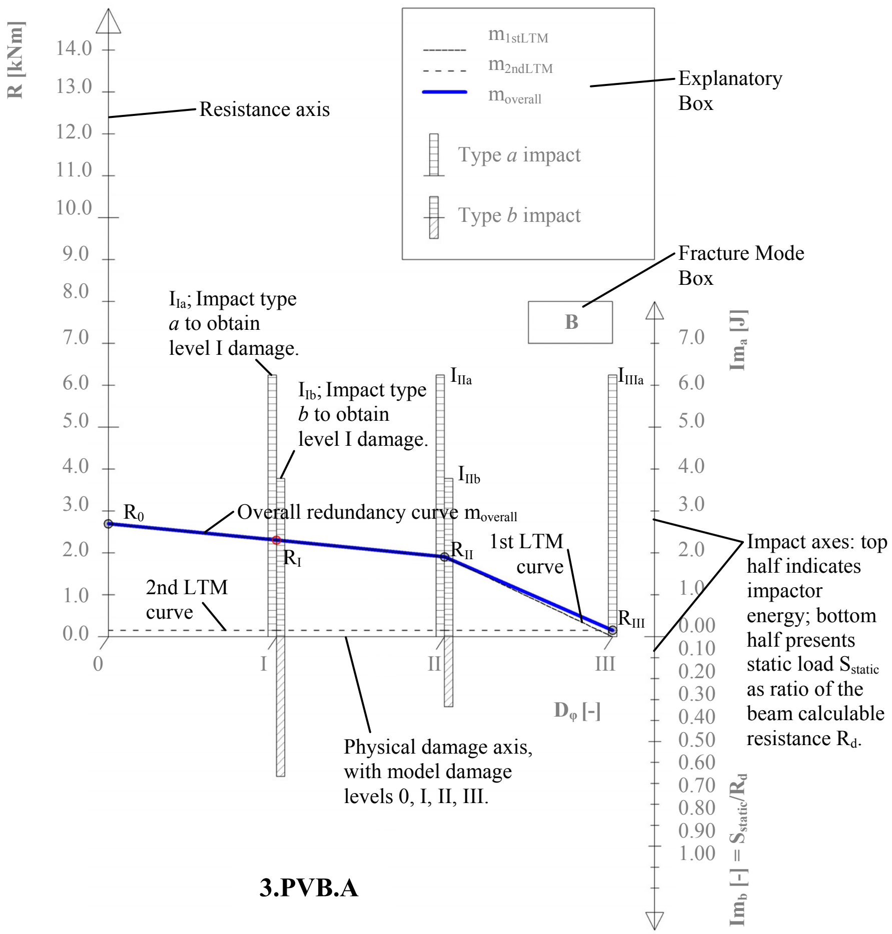

Figure 2: Example ESD of triple layer ('3'), PVB laminated ('PVB'), annealed ('A') glass beam. LTM = Load Transfer Mechanism.

2. Results: Element Safety Diagrams of 14 Glass Beam Designs

The ESDs for each beam design are presented graphically in Figures 3 – 16. In some cases, argumentation and/or interpolation has to be used to compensate for insufficient experimental results.

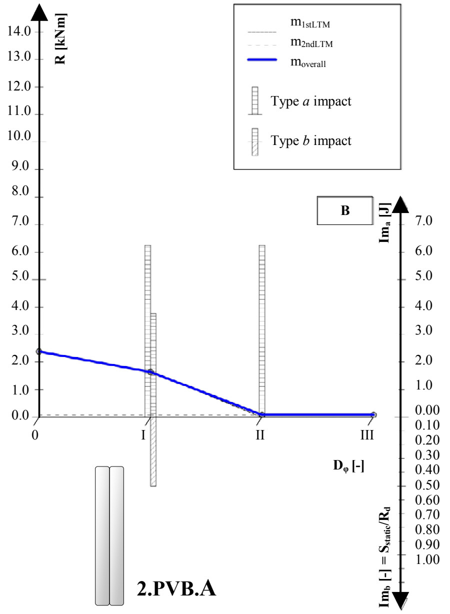

Figure 3: Element Safety Diagram for double layer, PVB-laminated, annealed glass beam.

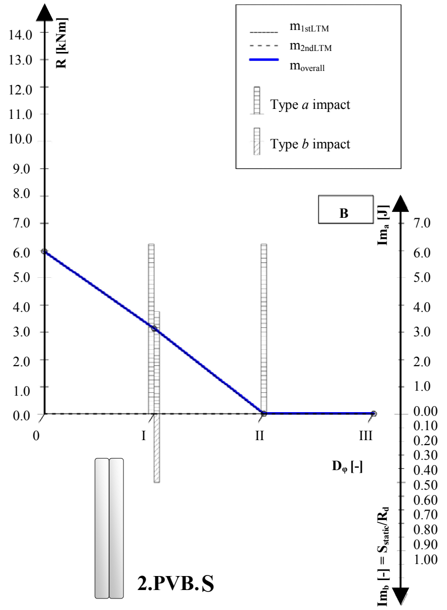

Figure 4: Element Safety Diagram for double layer, PVB-laminated, heat strengthened glass beam.

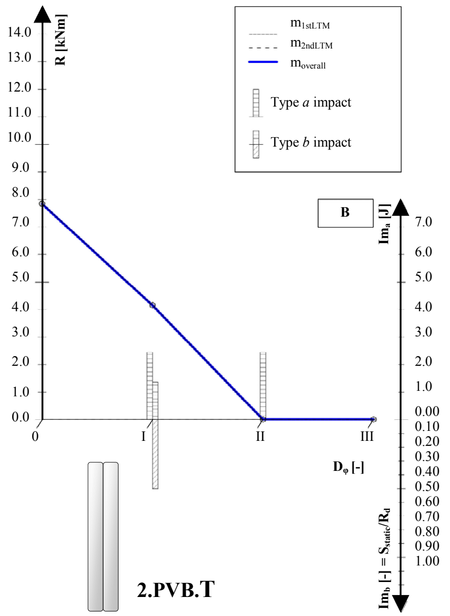

Figure 5: Element Safety Diagram for double layer, PVB-laminated, thermally tempered glass beam.

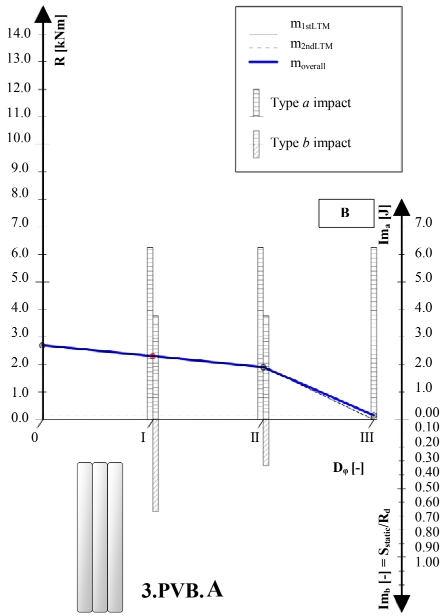

Figure 6: Element Safety Diagram for triple layer, PVB-laminated, annealed glass beam.

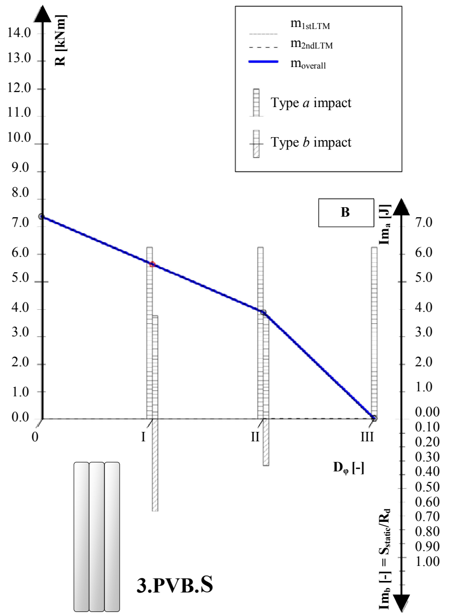

Figure 7: Element Safety Diagram for triple layer, PVB-laminated, heat strengthened glass beam.

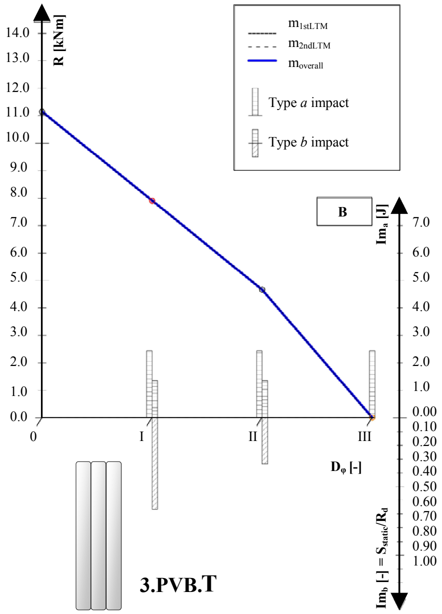

Figure 8: Element Safety Diagram for triple layer, PVB-laminated, thermally tempered glass beam.

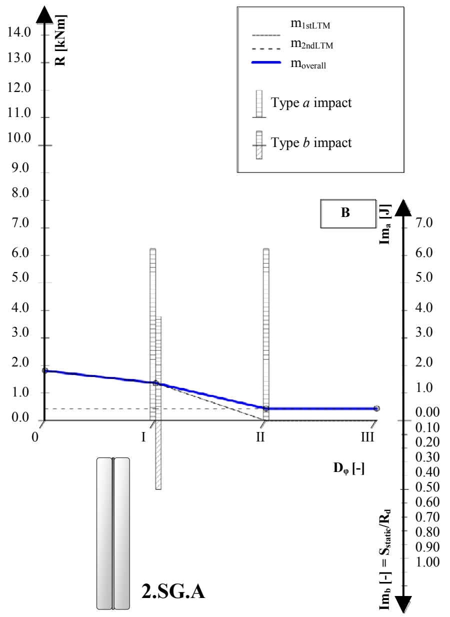

Figure 9: Element Safety Diagram for double layer, SG-laminated, annealed glass beam.

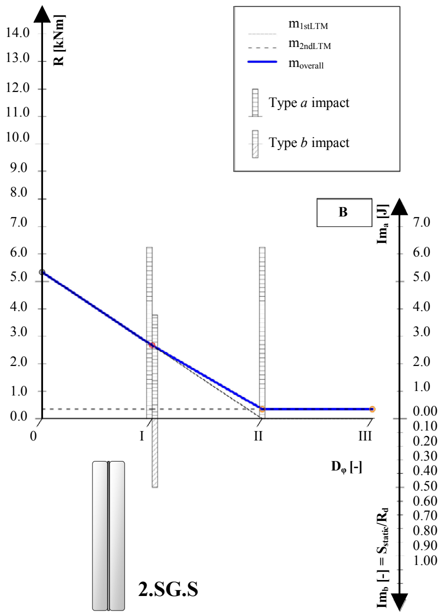

Figure 10: Element Safety Diagram for double layer, SG-laminated, heat strengthened glass beam.

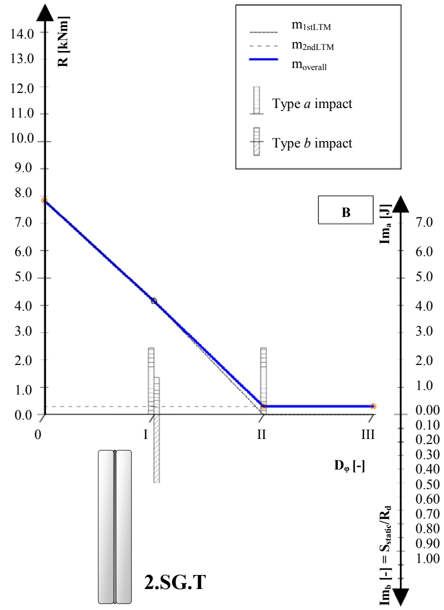

Figure 11: Element Safety Diagram for double layer, SG-laminated, thermally tempered glass beam.

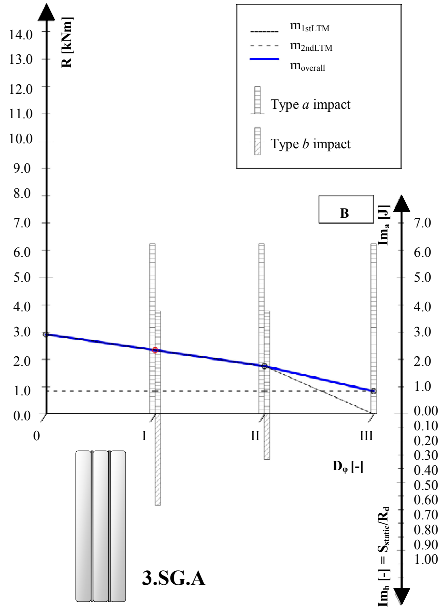

Figure 12: Element Safety Diagram for triple layer, SG-laminated, annealed glass beam.

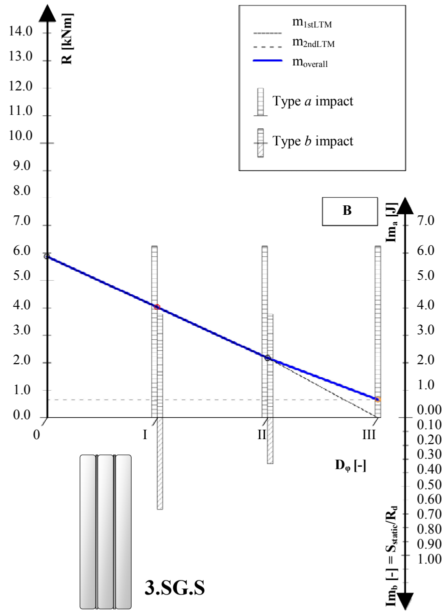

Figure 13: Element Safety Diagram for triple layer, SG-laminated, heat strengthened glass beam.

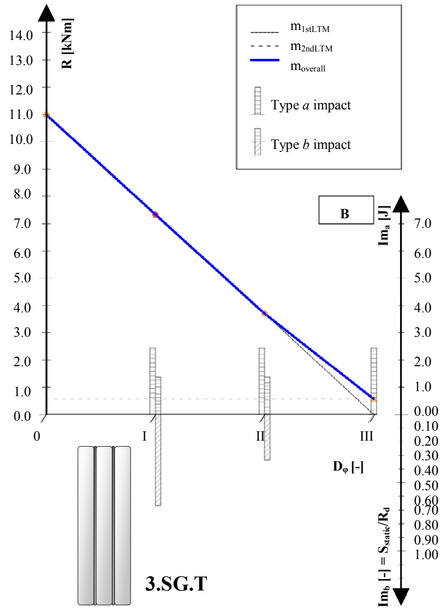

Figure 14: Element Safety Diagram for triple layer, SG-laminated, thermally tempered glass beam.

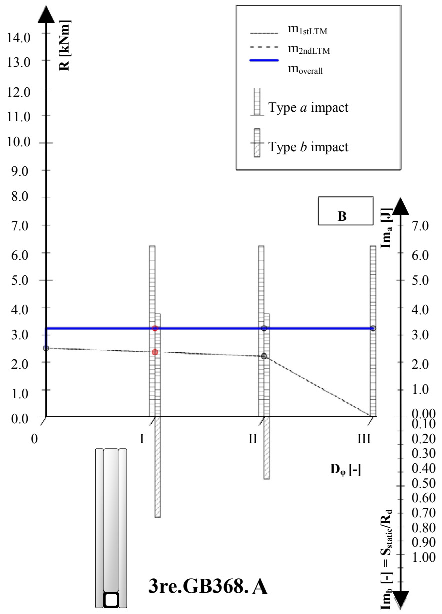

Figure 15: Element Safety Diagram for triple layer, GB368-bonded, annealed glass beam.

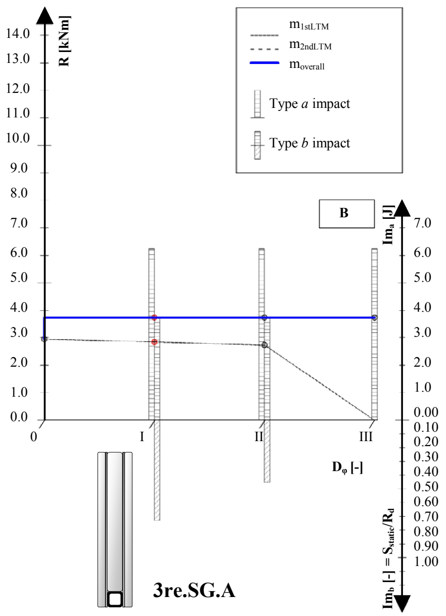

Figure 16: Element Safety Diagram for triple layer, SG-laminated, annealed glass beam.

3. Discussion

3.1. Impact and Damage Sensitivity

The damage sensitivity of laminated glass beams is independent of laminate type for the impact types applied in the experiments on which these ESDs are based (compare Figure 3 to 9, or 6 to 12). There is no significant difference in fracture pattern between PVB- and SG-laminated beams.

On the other hand, damage sensitivity does depend on the thermal treatment of a glass sheet. Much less impact is required to shatter a thermally tempered glass sheet than an annealed or heat strengthened one (compare, e.g., Figure 5 to 4 and 3). This applies for both impact types applied, with and without the presence of a static load. The impact only needs to penetrate the compressive layer in the glass where after the sheet will disintegrate itself by release of internal strain energy. Remarkably, the self-destructive mechanism *does not* occur with heat strengthened glass.

The presence of a static load significantly increases the physical damage an object impact induces (visible in all Figures 3 – 16). The impact energy to obtain a certain level of damage is reduced by approximately 40 % when a static load equal to the calculable strength of the remaining layers is present.

3.2. Post-failure Strength

The post-failure strength of the PVB laminated beams is small in all cases (Figures 3 – 8) Nevertheless, the annealed, heat strengthened, and thermally tempered beams present crucial differences. For all thermally tempered beams, the post-failure strength was less than their self weight. Heat strengthened beams could, on average, carry 1.5 times their self weight after failure, but, importantly, one of the three specimens on which this average was based had a post-failure strength lower than its self weight. Thus, it may be concluded that failed heat strengthened and thermally tempered PVB-laminated glass beams can carry practically no external loads. Only with annealed glass, at least some surplus resistance remains (Figures 3 and 6); 5.7 to 7.3 times their self weight for double and triple layer beams respectively.

Contrary to PVB laminated beams, glass beams laminated with SG all posses 2^{nd} LTMs with significant capacity (Figures 9 – 12). The post-failure strength is proportional to the amount of SG in the section, but also larger than could be expected based on the difference in thickness and tensile strength with PVB. The bending tensile stiffness of the laminate material plays a crucial role, as it determines magnitude of the compressive stresses that can build up in the broken glass.

Unlike the more common laminated beam designs, the beams with steel reinforcement (Figures 15 and 16) have a post-failure strength that exceeds the initial resistance R_0. This can be attributed to the 2^{nd} Load Transfer Mechanism, which develops after breakage of all glass layers: composite action between the (broken) glass in compression and the steel in tension. With the applied material proportions and (section) geometry, the post-failure strength is determined by the steel yield strength. It is likely even higher post-failure strengths can be obtained by applying more steel in a section.

4. Relative Overall Redundancy Curves

In order to be able to compare the failure behaviour of the various beam designs, the redundancy curves can be made relative to R_0, through $r_n = R_n / R_0$ (n = I, II, III). This is relevant because the calculable strength is also deducted from that value through the material partial factor ($R_d = R_{rep}/\gamma_M$) and it may, furthermore, be expected that dimensions of an element will be adjusted so that the actions will (almost) match the calculable strength (material efficiency). The relative redundancy curves have been shown in Figures 17 – 24.

Figure 17 shows the relative redundancy curves of the PVB laminated designs. A change in slope occurs in the curves for 2.PVB.A, 3.PVB.A, 3.PVB.S, and 3.PVB.T, indicating a non-linear relation between the reduction in unbroken layers and the resistance. This indicates the broken glass layers still effectively carry small compressive forces (effectively creating a T-shaped section). Thus, ignoring the broken layers in a resistance calculation of a damaged annealed glass beam seems safe and slightly conservative.

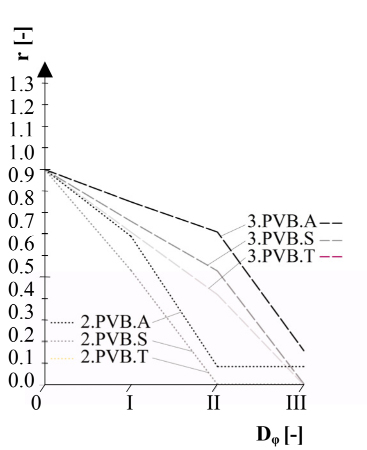

Figure 17: Relative redundancy curves for PVB laminated glass beams.

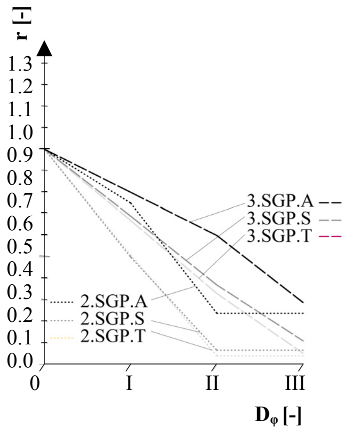

Figure 18: Relative redundancy curves for SG laminated glass beams.

The curves for 2.PVB.S and 2.PVB.T, on the other hand, run straight. This shows that the broken layers do not contribute to the element resistance anymore (probably because of a combination of fracture pattern density and low tensile stiffness (only one PVB layer). For these beams, ignoring broken layers seems allowable, albeit not conservative.

Of the heat strengthened and thermally tempered beams, the post-failure resistance (R_{III}) is low – but related to the initial resistance R_0, it practically becomes negligible ($0.1\ \% < r_{III,2/3.PVB.S/T} < 0.6\ \%$). The annealed beams (especially the triple layer ones) on the other hand, show their post-failure resistance r_{III} is not irrelevant, being in the order of 10-20%.

The relative redundancy curves for the SG laminated beams are shown in Figure 18. The change in slope as observed with most of the PVB laminated specimens, here also occurs with the annealed specimens. Of the heat strengthened and thermally tempered beams, too few specimens were available to determine this. The intermediate resistance values were obtained by linear interpolation. All designs provided significant post-failure strength, but because of its lower initial resistance, the post-failure strength of the annealed beams is, relatively, much higher than of the strengthened and tempered ones. Such an amount of post-failure strength could be relevant in a range of practical applications.

As with the PVB laminated beams, the post-failure resistance r_{III} of equally heat treated beams is higher for triple layer designs than for double layer ones, due to the increase of laminate in the section, which has little influence on the initial resistance R_0.

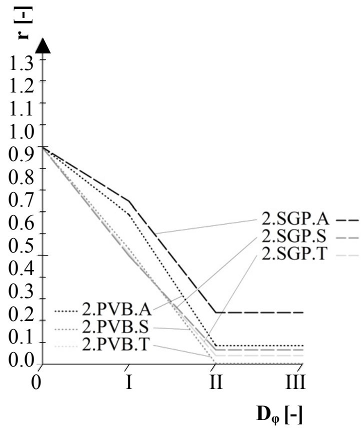

Figure 19: Relative redundancy curves for double layer glass beams.

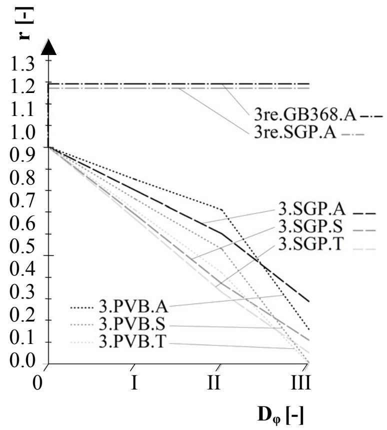

Figure 20: Relative redundancy curves for triple layer glass beams.

In Figure 19, the curves of the double layer beams are presented. Besides the fact that $r_{III,2.SG.A}$ clearly exceeds the r_{III} of the other designs, it is remarkable that $r_{III,2.PVB.A}$ is in the same order of magnitude (and even a bit larger) as $r_{III,2.SG.S}$ and $r_{III,2.SG.T}$ (also compare Figures 21 – 23).

Figure 20 shows the triple layer beam-curves. As with the double layer designs, the SG laminated, annealed glass beam has an r_{III} well above that of the other laminated beams. Here, also, $r_{III,3.PVB.A}$ exceeds $r_{III,2.SG.S/T}$. But none of these come close to r_{III} of the reinforced beams. The difference between $r_{III,3re.GB368.A}$ and $r_{III,3re.SG.A}$ is small, and not very important for the overall safety of the design.

In Figures 21 – 23, the relative redundancy curves are shown per prestress treatment (annealed, heat strengthened, thermally tempered). They clearly show the potential of annealed glass in terms of residual strength, especially in comparison to tempered glass, but to lesser extent also to strengthened glass. The large difference in relative residual resistance stems not only from the higher absolute residual strength of annealed glass beams, but also importantly from their lower initial strength, which positively influences the ratio between pre- and post-failure strength.

For comprehensiveness, the relative redundancy curves of all designs are presented together in Figure 24.

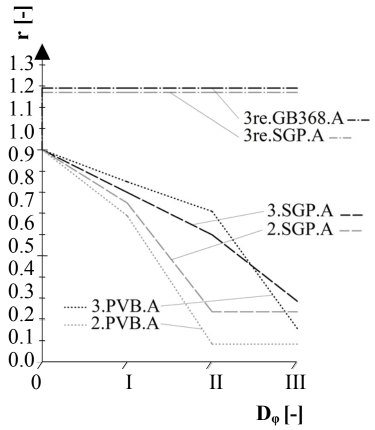

Figure 21: Relative redundancy curves for annealed glass beams.

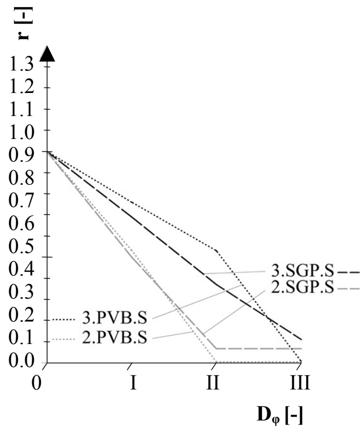

Figure 7.22: Relative redundancy curves for heat strengthened glass beams.

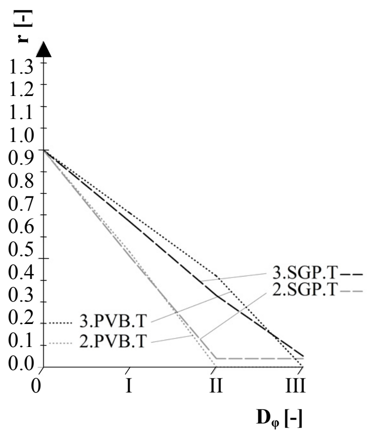

Figure 23: Relative redundancy curves for thermally tempered glass beams.

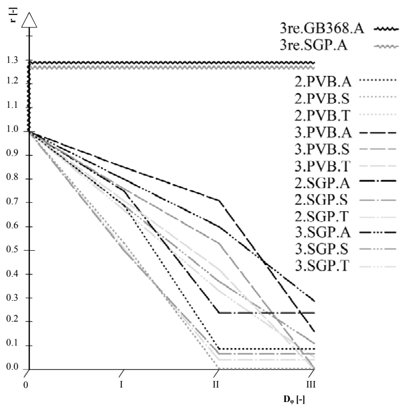

Figure 24: Relative redundancy curves for all glass beams presented in this Chapter.

5. Safety Comparison

Obviously, from a safety point of view, the triple layer designs perform much better than the double layer ones. They are harder to damage to failure, as they require an extra impact. When a physical impact is considered to be governing, the fact that the inner layer is well protected by the outer ones should weigh heavily in the safety assessment. Receding the inner layer or protecting it with some kind of covering will make it even more difficult to cause damage. In a triple layer laminate, only erroneous manufacturing and handling or faulty joining then seem likely damage causes.

Besides the lower damage sensitivity, the redundancy of triple layer beams is also much better. At model damage level II, they can still rely on a portion of unbroken glass and thus much higher residual strength. At level III, they usually profit from more laminate material in the section, compared to double layer designs – although more layers than standard could be applied in double layer beams, nullifying this latter advantage.

As expected, the safety of the SG laminated beams is significantly higher than of the PVB laminated designs – even though their damage sensitivities are equal. Their safety stems particularly from their post-failure strength. The triple layer annealed glass beams laminated with SG have an r_{III} of close to 30 %. By doubling or tripling the number of SG layers, it may well be possible to arrive at r_{III} values close to 100 %.

Annealed and heat strengthened glass perform similarly with regard to damage sensitivity from physical impact. However, annealed glass provides higher post-failure strength, both relatively and absolutely. Annealed, PVB laminated beams even have a higher relative post-failure strength r_{III} than heat strengthened, SG laminated ones. On the other hand, heat strengthened glass is more resistant to some other impacts like thermal stress. Thermally tempered glass behaves poorly compared to annealed and heat strengthened glass. It has a much higher damage sensitivity and leads to less post-failure strength.

From a safety point of view, the reinforced beams out perform the other designs by far. They pair very low damage sensitivity with very high redundancy. Although their sensitivity to physical damage is comparable to that of the laminated beams, the model damage levels have little influence on the resistance. Furthermore, the presence of the reinforcement profile makes it very difficult to actually damage the inner layer. With the resistance of the secondary Load Transfer Mechanism (i.e. the one that is activated after failure = breakage of all glass layers) consistently above that of the primary one, the amount of damage has practically no influence on the total load carrying capacity. Importantly, *this justifies effectively using the complete glass section in engineering calculations* (whereas with other beam designs, additional layers may have to be added).

Finally, it should be noted that the safety assessment is highly dependent on the impact that is considered to be governing; some designs are less sensitive to one type of impact, while being more prone to another type.

6. Acknowledgements

The author gratefully acknowledges the material contributions by the van Noordenne Groep, DELO GmbH, and DuPont.

7. References

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