Towards a combined probabilistic / consequence-based safety approach of structural glass members

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Glass is generally considered to be an unsafe material to use in building structures. To limit the risk associated with structures, Dutch and European codes focus on the probabilistic approach. It will be shown that this is insufficient for structures in general, and for glass structures in particular. Much more than common structural materials like steel and reinforced concrete, glass is highly susceptible to a wide range of incidents causing glass breakage. Hence, the question should not just be 'when will the glass break?' (probabilistic approach), but also 'what will happen when it does?' (consequence-based approach). Analysis of projects realized in practice show that structural engineers are indeed aware of this. They use varying strategies, like laminating and providing alternative load paths, to limit the consequences in case of glass failure. However, such strategies are applied to varying extent, depending on the experience and opinion of the engineer, the location, the structure type, and probably on many more factors. The premises and a priori requirements applied by either engineer or governing bodies with regard to the consequences of glass failure, are not formulated explicitly, nor in building codes nor in literature. At best, they remain implicit. Therefore, an explicit combined probabilistic/consequence-based safety approach is proposed for structural glass members. The consequence-based part of such a combined approach sets specific requirements to the residual strength of structural glass members for a certain period of time, at prescribed levels of damage. The concept of Member Consequence Classes (MCC) is introduced, in order to be able to differentiate requirements for members based on their role within a structure and the function and accessibility of the structure at hand. The presented approach allows for an open discussion on the required level of residual strength at varying levels of damage. Furthermore, it provides a basis for comparing design options in terms of safety and it allows for the development of standard structural glass members with a proven level of safety. Finally, because it sets requirements for the application of structural glass in any (building-) structural application, it provides a fundamental basis for the development of structural glass beyond the existing small scale glass structures like entrances, pavilions and conservatories.

Keywords: Structural glass, safety, risk, probability, consequence, damage, residual strength

1 Introduction: structural properties of glass

Glass shares its unique characteristic of transparency with very few other materials. The specific aesthetic effect transparency creates, makes it a favourite material among architects, leading them to consistently push the limits of the applicability of glass. Thus, it is no wonder that there is a strong, ever increasing desire to use glass also for building structures, thereby dematerialising just that part of the building responsible for keeping it up. However, its brittle failure behavior makes glass not an obvious choice as a structural material, even though it has relevant strength and stiffness.

The brittle behavior of glass is caused by the fact that by definition (glass is an amorphous solid, [1]), it has neither a crystalline structure on molecular level, nor large side strands on the molecules which may interlock when stressed (as happens in polymers like polycarbonate). In a way, a piece of glass is just a huge continuous grid of molecules. Glass, therefore, does not yield, neither globally nor locally, making it sensitive to peak stresses that may be the result of a wide variety of causes ranging from (micro scale) surface defects to (macro scale) detailing errors. Another consequence of the molecular structure is that there is no mechanism present in glass that may stop the growth of a crack once it has started. Furthermore, glass has an extremely low impact strength. Crack growth through a piece of glass costs very little energy because it has very low surface energy. The molecular bonds are relatively weak because of the electronically polar array.

This leads to several consequences that are disadvantageous to the use of glass in building structures.

- The load at which individual pieces of glass will break, shows a large scatter (the coefficient of variation is typically 10 – 30 %, [2]).
- Glass breaks suddenly. There is no inherent warning mechanism present which might point to immanent failure.
- Glass breaks completely. Once a crack has started, usually it will not stop until it has reached the edge of the glass piece, even when the exerted amount of energy was relatively small and brief (i.e. when the exerted stress is removed).

Apart from these structurally unsafe properties, the shards into which glass will break have such sharp edges that they will pose an immediate risk to the personal safety of people. Further considerations on this aspect, however, fall outside the scope of this article, which focuses on structural safety. The specific material behavior of glass calls for special attention to guarantee structural safety.

2 Safety approach in structural engineering codes

The concepts ‘safe’ and ‘safety’ can have a very broad meaning. Generally speaking, a piece of engineering is considered to be safe when it is unlikely that it will cause serious damage or injury. To quantify safety, the notion of risk has been introduced, popularly defined as the product of probability and consequence, eq. (1). In reality, the correct mathematical formulation is more complex, [3], as it may involve the law of total probability, eq. (2).

Nevertheless, (1) suffices for the argument presented in this paper. It clearly points out that risk is basically dependent on two components: the probability that something will happen and the consequence when it does. Thus, risk can be lowered by decreasing either or both of these components.

$$R_F = C_F \cdot P_F \tag{1}$$

$$R_F = \sum_i P\{H_i\} P\{F|H_i\} C_{F_i} \tag{2}$$

With: R_F = risk associated with the failure of a piece of engineering; P_F = probability of a failure event; C_F = the consequence of a failure event; H_i = Occurrence of situation *i*; *F* = Occurrence of failure event.

2.1 *Codes on the general basis of design of building structures*

The basic requirements towards building structures in the Netherlands are defined in the NEN 6700 [4]. In this code, the maximum failure probability is limited primarily by requiring a structure to meet a minimum reliability index β, which is defined as the probability that an ultimate limit state or a serviceability limit state is exceeded during the reference life time of the structure (clauses 5.3.1 and 5.3.2). The required reliability index β is dependent on the safety class into which the structure can be categorized. The safety class is determined by the consequences of collapse of the structure in question. The higher the safety class, the higher the required value for β (note that a high value of β coincides with a low failure probability). Thus, this is a requirement towards the probability component of the risk function (1), the value of which is dependent on the consequence component that is considered a given. Whether a structure meets the reliability requirement can be determined on four levels of probabilistic analysis, ranging from deterministic to fully probabilistic. The semi-probabilistic method which uses partial factors to account for uncertainty around variables is the minimum level of probabilistic analysis allowed by the NEN 6700, and the one most often used.

The NEN 6700, in clause 5.3.3, also states that collapse of a single component should not lead to excessive damage. It specifies that damage should remain localized after collapse of a part of the structure and that essential parts of the main load bearing structure should have an extremely small probability of collapse by taking preventive measures and paying specific attention to the quality of the design and construction process. Thus, this clause pays attention to the consequence aspects of risk. Independent of the probability of the occurrence of a failure, it sets limits to the acceptable consequences of such a failure. It requires design measures to achieve this, rather than adjusting stress levels by changing (section) dimensions. However, this formulation remains quite general as well as qualitative rather than quantitative.

To check whether a structure meets the reliability requirements, extensive rules are laid down in NEN 6702 [5], which defines the actions on structures, and several material codes, giving rules of how to check a designed structure against those actions. This method of checking occurring stresses against material strength is primarily a probabilistic one. The material codes also contain requirements related to the consequence aspect of risk, but they are usually not clearly recognizable as such. They turn up as design or detailing rules that aim at allowing the supposed plastic behavior of a material to actually develop and, by doing so, avoiding brittle failure. However, besides the general requirements formulated in clause 5.3.3 in NEN 6700, the background to these rules is unclear and the desired behavior not explicitly formulated. It is therefore questionable if they are consistent, especially when considering different materials.

At the moment, the Dutch codes coexist with codes that have been developed in European context by the CEN. Basic requirements towards building structures are formulated in NEN-EN 1990 [6]. This code sets requirements to the reliability of structures similar to those in the NEN 6700. With regard to the consequences of failures, the NEN-EN 1990 is more extensive. In 4(P) under clause 2.1, it is stated that a structure should not be disproportionately damaged by explosion, impact or human error. Identifying human error as a cause of damage is important because it is virtually impossible to describe by probabilistic means. Not only is there not enough data available, it is also unlikely that the effects of human error would fit a known statistical distribution – even though there may be some consistency in the mistakes we make. Sub clause 5(P) names several strategies that can be deployed to limit or avoid potential damage. Avoiding as far as possible structural systems that can collapse without warning is one of them.

Although being more specific than the Dutch codes, these requirements are still quite generally formulated. However, part 7 of Eurocode 1 (NEN-EN 1991-1-7, [7]), deals with the structural resistance both to identified accidental actions, like vehicle impact and explosions, and unspecified failure causes in detail. Especially the acceptance in the code that 'unspecified failure causes' may occur, is important because it calls for a consequence based safety approach. And indeed, clause 3.3 of NEN-EN 1991-1-7 describes strategies to be applied to the design of building structures in order to limit the extent of localised failure of whatever cause: key structural elements should be designed to withstand a (large) accidental action, and the structure should be designed in a way that failure of a local member will not endanger the stability of the structure of a significant part of it. Design and detailing rules should provide an acceptable robustness for the structure.

The informative annex A of NEN-EN 1991-1-7 gives a guideline to design for consequences of localised failure in buildings from an unspecified cause. It categorizes building types into consequence classes (CC) CC1, CC2a, CC2b and CC3, depending on the severity in case of collapse (1 is low consequence, 3 is high consequence). The extent of the measures that should be taken to avoid disproportionate collapse are dependent on consequence class and range from no further measures (CC1), to a complete systematic risk assessment (CC3). Off course, it can be debated what amount of damage can be accepted, and when damage will be 'disproportionate'. NEN-EN 1991-1-7 proposes a limit of 15% of the floor area or 100 m^2, whichever is smaller, of localised damage caused by failure of a structural column on each of the two adjacent storeys. It furthermore provides guidelines for horizontal and vertical structural tyings to ensure the robustness of the structure.

The quantitative requirements with regard to the consequence of a local failure are still relatively limited compared to all requirements regarding the probability of a failure. Nonetheless, contrary to the Dutch codes, the European codes provide more explicit general requirements on how those consequence related requirements should be met. However, it should be noted that both general requirements in the NEN-EN 1990 and the rules and guidelines in NEN-EN 1991-1-7 focus on the (complete) structure.

*2.2 **Structural glass codes***

At the moment of writing, there is no definite Dutch code on the structural use of glass. Of the NEN 2608 series, only part 1 [8], dealing with wind loading on vertical glazing, has been accepted. Several provisional versions of part 2 [9] (wind loading, snow and self weight on non-vertically installed glass) have been published. A definitive version of NEN 2608-2 is scheduled for mid-2007. Parts 3 and 4, concerning specific loads on non-vertical glazing accessible for maintenance and glass separations for floors respectively, are still in preparation. The scope of NEN 2608-2 excludes glass in primary load carrying applications (like beams and columns) and even in floors. Nevertheless, it usually serves as a starting point to evaluate glass structures because of a lack of a material code for glass in structural applications.

To check whether a non-vertical glazing meets the structural requirements, NEN 2608-2 only requires a stress check as eq. (3). Furthermore, it provides rules to calculate the maximum bending tensile stress and the bending tensile strength of the glazing. But it does not specify any requirements with regard to the consequence of a failure.

$$\sigma_{i;d} \leq f_{mt;u;d} \tag{3}$$

On European level, a provisional code for structural glass, the NEN-EN 13474, has been circulating for 8 years but was withdrawn early 2007. This code had a wider scope than the NEN 2608-2. In principle, it was applicable to all glazing required to resist actions according to NEN-EN 1991-2 that are acting normal to the surface. This effectively ruled out beams and columns. As the NEN 2608-2, the NEN-EN 13474 focused on checking the design stress against the bending tensile strength of the glass. However, it did not completely ignore the consequence component of risk because it stated in clause 5.1 that breakage of the glazing should not result in further damage if the glazing is part of the ‘supporting structure’. However, how this general remark was to be interpreted was not elaborated further.

The German structural glass code DIN 18008 [10], of which a provisional version has been published in March 2006, appears to be the first to extensively treat the consequence aspect, by requiring glazing structures not only to be able to carry actions on it during its reference life time with a certain level of probability but also demanding sufficient residual strength (Resttragfähigkeit) for certain structures or installation situations. It therefore defines residual strength as the capacity of a glazed construction to remain sufficiently stable in case of glass breakage. It rightfully states that this can not be realized by applying a safety factor as this would influence the probability of failure, not the consequences, should one occur.

Thus, from the analysis of the safety approach concerning structural glass in Dutch, European, and German codes, it may be concluded that:

- Within the Dutch general structural codes, there is a focus on the probability aspect, although NEN 6700 gives some general requirements to the consequence aspect. Consequence based requirements return in the codes as detailing rules, aiming at allowing the plasticity of the common structural materials to actually develop. Their background remains unclear.
- The European general structural codes follow a combined probabilistic/consequence-based approach. More or less specific requirements with regard to post-incident behavior

are formulated and strategies are proposed to obtain the required behavior. However, this is limited to the structural level, i.e. only the consequences of incident on the complete structure are being tied to rules. The material codes provide detailing rules similar to the Dutch ones.

- The only existing Dutch (provisional) structural glass code is limited in scope, and only requires a stress check. Thus, it only pays heed to the probability aspect of risk.
- The European provisional glass code has been withdrawn. It was also limited in scope, although not as narrow as the Dutch one. It required a stress check and gave some very generally formulated requirements concerning limitation of consequence of individual glass pane failure. However, it lacked specific a priori requirements. The requirements of 1990 and 1991-1-7 were not directly applicable because they are more directed towards structure level. Furthermore, there were no real strategies given how to fulfill consequence requirements.
- The German provisional structural glass code seems to be the first to explicitly introduce consequence-related requirements by requiring residual strength in case of glass breakage.

Thus, in the codes relevant to structural glass, there has been an emphasis on the probability component of the risk function. Recent developments show a growing interest in the consequence component, which has been underexposed until now.

3 Limits to a probabilistic approach

Although the probabilistic approach is a powerful tool in assessing and minimizing the risk of structures, it has its limits. For a full probabilistic analysis, it would be required that all relevant data concerning structural properties (e.g. material composition, material quality, geometry) and actions on that structure (self weight, static, semi-static, dynamic, shock/impact) are known, so that they can be described statistically. Usually, this is impossible. In practice, this is solved by using approximations and estimations based experience from the past and (limited) research. For common structural materials with a constant quality over large periods of time, well known behavior and extensive experience by people working with them combined with common static or semi-static actions, these approximations will work quite well. In structural engineering codes, the focus is on those kinds of actions, combined with a check of more infrequent actions like impacts of which the force can still be relatively well be assessed.

The reliability of a structure is often expressed as the probability of 1 in *n* years that the structure will fail. Such a formulation has a deceivingly tangible ring to it. But it is a theoretical reliability that bears no immediate relation with a real failure probability, not only because of the approximations used in the probabilistic analysis and the assumption that they will remain valid throughout the reference life time, but even more so because in reality, failures are hardly ever caused by those actions applied in present probability analysis [11]. Instead, failure can be caused by a number of different deficiencies and errors, many of which are not even inside the domain of the structural engineer. Technical errors may be a lack of consideration for tolerances, design errors in structural details, unanticipated loading or insufficient stability during construction and a lack of communication between designer and builder [11]. However, the prevailing political, financial, scientific, professional and industrial conditions may have an overriding effect [12]. Especially financial pressure can cause errors to be made and warning signals to be ignored. Also, organisational failures may cause information not to arrive at the right person [13]. Actual failure is usually not caused by a single error but the consequence of a conjunction of multiple deficiencies. Such failure causes are practically impossible to describe statistically. Hence, the calculated reliability of a structure is useful to compare structural designs with each other and to a theoretically allowable level of risk, but has limited meaning in terms of real risk.

When using common structural materials, there is a margin between failure and collapse. Failure relates to a loss of structural, practical, aesthetical or other function, while collapse is the tumbling down of (part of) the structure. This is a distinction that is not explicitly made in the codes. In common structural materials like steel and reinforced concrete, local failure and overall collapse do not coincide upon overloading. This is most clearly illustrated by steel. In stress checks, the yield strength of steel is used. Thus, a steel member is considered to have failed (i.e. have reached it ultimate limit state) when it yields, although local yielding may occasionally be accepted as a settling mechanism. However, collapse will not occur until the ultimate (tensile) stress is reached. Depending on the steel quality and the (detail) design, the ultimate strength of steel may range from 100 to 150 % of the yield strength. Even if the nominal yield strength is exceeded (failure), the consequences will most likely remain limited because of this reserve. Similar observations, though not as obvious, hold for reinforced concrete because it also heavily relies on the plastic behavior of steel.

This means there is a considerable safety in steel structures that stems from the difference between failure and collapse, which implicitly constitutes the consequence limitation on member level in a steel structure. Because of it, steel structures constructed according to NEN-EN 1991-1-7 and the Eurocode Steel posses a double redundancy, both on member level and level of the complete structure (Table 1).

Table 1: Safety strategies in a steel structure.

Level ➔ **🡇 Approach**	**Individual member**	**Structure**
Probabilistic	Explicit reliability (probability of exceeding uls)	Explicit reliability (probability of exceeding uls)
Consequence-based	Implicit redundancy through material behavior (implied in design rules that aim at allowing plasticity to develop).	Explicit redundancy through requirements in NEN-EN 1991-1-7.

The importance of making explicit this difference between failure and collapse is that the material behavior of glass is such that, contrary to steel, failure does coincide with collapse. Therefore, the implicit redundancy on member level present in steel structures, disappears in glass structures (Table 2). NEN 2608-2 formulates no requirements and NEN-EN 13474 only formulates a very general requirement. Only DIN 18008-1 seems to discern this problem by requiring residual strength in case of glass breakage.

Table 2: Safety strategies in a glass structure.

Level ➔ **🡇 Approach**	**Individual member**	**Structure**
Probabilistic	Explicit reliability (chance of exceeding uls)	Explicit reliability (probability of exceeding uls)
Consequence-based	No redundancy through material behavior.	Explicit redundancy through requirements in NEN-EN 1991-1-7.

To this observation it should furthermore be added that glass, due to its material properties, is much more than common structural materials, susceptible to all kinds of incidental actions, deficiencies and errors that are hard/impossible to describe statistically. Failure causes (and thus collapse) can include [14, 15]: detailing errors (causing stress concentrations), construction and handling errors, product errors, alkaline degradation, stress corrosion, nickel sulphide inclusions, thermal stress, fire, impact (soft body or hard body), and scratching.

This, together with the absence of material based redundancy behavior makes it extremely important to explicitly consider the consequence component at member level of the risk associated with glass structures. It is remarkable that such considerations are not only absent in most structural glass codes, but also hardly ever explicitly formulated in scientific literature concerning structural glass. Nevertheless, from structural glass projects realised in practice, it is immediately clear that engineers indeed do recognize the dangers of immediate collapse upon failure, and adjust there designs in ways to avoid this.

4 Safety approach in structural glass projects

Combining single glass plies into multiply laminates with adhesive interlayers is the single most important strategy applied in practice to avoid sudden collapse of a structural glass member. The basic argument behind the application of this technique is that if one ply breaks through whatever cause, the remaining ply/plies will still be able to carry a certain load while simultaneously ensuring that the glass shards will stick to the laminate, thus avoiding personal injuries. But beyond this basic and valid argument, a number of questions arise, such as:

- how many layers should be used?
- should there be reckoned with failure of a single glass ply or of multiple plies or perhaps even of the entire glass section?
- what action should be reckoned with after failure / what should be the strength of the remaining ply/plies?
- should the glass be prestressed?
- what kind of interlayer should be used?

These questions are answered differently in different projects. And it is unclear on what grounds decisions are being made. Although literature on glass projects usually describes the chosen solution, the argument behind such choices is often partly or completely omitted. The number of layers of glass can vary between two and more then ten in a section. Applying three layers is probably most common. In some projects, only breakage of one ply is considered, while in others breakage of at least the two outer plies is taken into account. Such assessment is highly dependent on the accessibility of the structural member. Failure of the complete section is not usually thought to be realistic, but in some projects it is being reckoned with. Also regarding the action on the member after failure, approaches differ significantly. While in some projects, carrying the self weight of the member is enough as alternative load paths are activated, in others the actions belonging to the serviceability limit state are considered for the post-failure situation, but reckoning with the full ultimate limit state action is also not uncommon. Off course, such considerations are of prime importance to the amount of material that is being used.

Thermally prestressing glass is in itself not a strategy to improve the post-failure behavior. Instead, it influences the probability of failure. Prestressed glass is less sensitive to a number of failure causes (surface impact, thermal stress, general loading), while being more sensitive to some others (hitting on the edge, nickel sulfide inclusions). Fully prestressed glass (thermally toughened) has significantly worse post-failure behavior than semi-prestressed (heat strengthened) or annealed glass, because of its breakage pattern into very small fragments. Thus, an optimum has to be found between initial resistance to failure causes and post-failure behavior. Again, the chosen solutions in practice vary significantly.

Perhaps the most important parameter when determining the post-failure behavior of a laminate glass member is the choice for the kind of interlayer. Resins have the practical advantage of being able to fill wide cavities, but their strength is so low, that a resin laminated member will collapse under its self weight if all glass plies break. The most commonly used interlayer, PVB foil, has better structural properties but it is still so soft that it will deform enormously when all glass in the laminate has been broken. This may cause such an element to sag out of its supports, to be torn under its self weight or to be cut by the glass fragments it is holding together. Especially when combined with thermally toughened glass, PVB provides very little post-failure strength when the complete glass section breaks. New ionoplast interlayer foils like Sentry Glass Plus from DuPont, provide much higher strength and stiffness, and are thus able to keep carrying significant loads even after breakage of the complete glass section [16]. However, stability problems may occur when such a stiff thin foil is loaded in a way other than membrane action. Occasionally, laminates in which layers of transparent polymers like PMMA were included, have been applied [17]. Off course, such laminates may provide significant post-failure strength, depending on strength of the polymer.

Another strategy to obtain post-failure strength is by reinforcing a glass member (up until now only beams) with a strand of another, stronger material. The glass roof of the Thermal Spa in Badenweiller, Germany contains glass beams of three layer laminated, toughened glass [18]. The middle ply is a bit shorter than the outer ones, creating a groove at the bottom side. An aluminium U-profile has been placed in this groove and a stainless steel cable has been fed through the profile. The cable has been post tensioned. Although it is reasoned that the profile and cable should keep the glass together in case of glass failure, breakage of the whole section will most likely result in an almost complete loss of strength because the tempered glass will break into small fragments. In a small loggia in Arquà Petrarca in the province of Padova, Italy however, a concept of reinforcement has been applied in a more consistent manner [19]. Here, beams from laminated annealed glass are reinforced with a strand of carbon fibre. When the complete glass section breaks, the broken glass acts as a compression zone while the carbon fibre transfers tensile forces, much like reinforced concrete. At the faculty of Architecture of the TU Delft, several prototype glass beams have been presented in recent years [20, 21,22]. These prototypes consist of layers of annealed glass reinforced by small stainless steel profiles. By adjusting the strength and stiffness of the glass section to that of the steel section, post-failure strengths (after breakage of the complete glass section) of over 140 % can be obtained.

It is noteworthy that all designs which incorporate consequence-based safety measures, involve the use other materials besides glass, thus creating composite members. This holds for every design, ranging from ordinary PVB-laminated members, to innovative stainless steel reinforced beams.

It is clear that in practice there certainly is attention for limiting the consequences of a failure. At least some kind of failure is generally reckoned with. However, consequence based safety requirements are not formulated a priori (at least not publicly). Because the explicit safety requirements on member level only concern probability, it can not be properly assessed if the required level of safety is achieved in a specific design. Furthermore, design options can not objectively be compared and it is not clear what experiments should be performed to prove the safety of a specific design. Finally, the lack of clearly formulated requirements concerning post-failure behavior, make it difficult to discuss structural safety of glass members.

5 Towards an explicit combined probabilistic/consequence-based approach

To address these problems, a set of a priori formulated consequence-based safety requirements is proposed, based on the post-failure strength of structural members for a certain period of time under different amounts of damage. When used in coherence with the existing probabilistic stress checks, an explicit combined probabilistic/consequence-based safety approach results, appropriate to assess the risk of glass structures.

5.1 ***Parameters***

A consequence based safety approach aims to minimize the risk associated with structural failure by controlling the consequences of a failure. Principally, failure is taken as a given. The consequence-based approach to the safety of glass structures here proposed, seeks to limit the consequences of failure of a structural member by requiring the member to retain a certain amount of strength for a certain period of time after the failure has set in. Thus, it can be avoided that failure coincides with collapse.

Failure of a glass member can occur in different forms. A three layer laminate beam (Figure 1) is considered ‘failed’ when all layers are broken, but also when only one layer is broken. Since the latter is more likely to occur than the former, it is reasonable to differentiate between the post-failure requirements for different failure cases. To be able to make such distinctions, the concept of glass damage D_{glass} is introduced as the third parameter by which the consequence-based safety requirement is defined (besides post-failure strength and time). Generally, damage can be defined in terms of residual strength after failure, eq. (4). This definition is maintained in the R6 procedure for steel vessels, [23]. However, this definition is not entirely suitable to apply in the method here presented. Rather, glass damage is defined in terms of loss of structurally functioning glass in the critical cross section of the member. The total glass section area is equal to the sum of the frontal area of cracked glass plus the frontal area of uncracked glass in a section, Eq. (5), Figure 2. Glass damage can than be defined by Eq. (6).

$$D = 1 - \frac{S_{res}}{S_{fail}} \tag{4}$$

$$A_{tot} = A_{fr,unc} + A_{fr,c} \tag{5}$$

$$D_{glass} = 1 - \frac{A_{fr,unc}}{A_{tot}} = \frac{A_{fr,c}}{A_{tot}} \tag{6}$$

With: D = Damage; D_{glass} = Glass damage; S_{res} = Residual strength; S_{fail} = Failure strength; A_{tot} = Total glass section area; $A_{fr,unc}$ = Frontal section area of uncracked glass (fig. 2); $A_{fr,c}$ = Frontal section area of cracked glass.

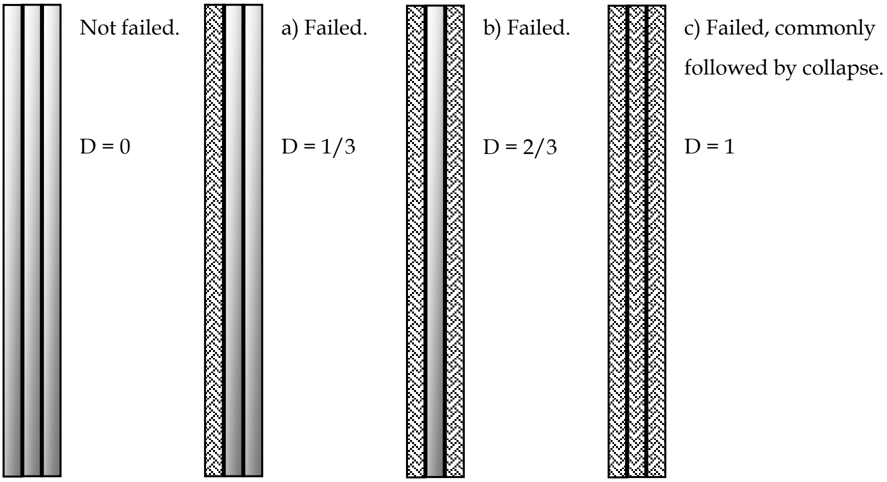

Figure 1: Failure of a three layer laminate glass beam, with different levels of damage: a) One outer layer broken, b) All outer layers broken, c) All layers broken. In all stages the beam can be considered to have failed. In an ordinary PVB-laminate beam, stage c) will also lead to collapse.

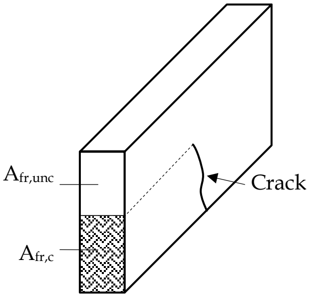

Figure 2: Frontal cracked and uncracked area in a glass section

For the purpose of this paper it is most practical to formulate the amount of damage in terms of cracking of 1 to *n* layers of glass, were *n* = the total amount layers in the cross section. For the purpose of clarity, the layers are considered to have an equal cross section area. The total section area can than be written as eq. (7). The consequence-based approach requires explicitly considering all stages of damage from nothing to complete loss of the glass section. Although damage does not necessarily have to coincide with a natural number (1, 2, 3, ..) of broken layers, nor does it have to occur in one moment in time, it is in line with the crack growth behavior in the material to consider these demarcations, rather than for example a percentage of the section. The crack growth speed also makes it natural to assume breakage to occur in one moment in time. Thus, eq. (6) can be rewritten as eq. (8) in which *d* is the damage factor for the number of cracked layers that will have to be considered (see Paragraph 5.2.1).

$$A_{tot} = nA_n \tag{7}$$

$$D_{glass} = \frac{dA_n}{A_{tot}} \tag{8}$$

With: n = number of layers in glass section; A_n = Section area of one layer; d = damage factor (i.e. number of cracked layers to consider).

By formulating requirements in terms of damage-dependent post-failure strength, it is guaranteed that even in case of failure, a predefined load can still be carried by the member without collapse. Thus, the consequences for personal safety and for the rest of the structure remain limited. The time component is introduced because it is not necessary for any glass member to have post-failure strength for an infinite amount of time. The three parameters by which the consequence based requirement is defined (damage, strength, time) can be outlined along three axes (Figure 3). The damage factor *d* can be outlined along the same axis as the glass damage D_{glass}. The minimum post-failure strength can now be defined as a 3D shape (Figure 4) in the D,S,t-diagram.

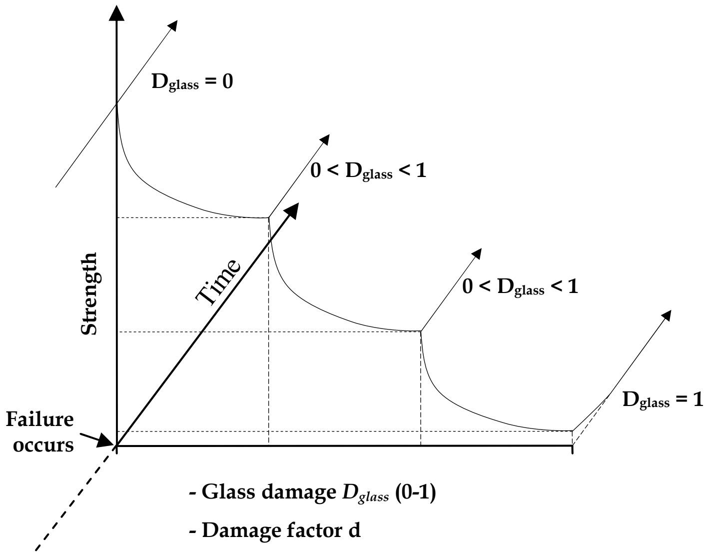

Figure 3: Parameters by which a consequence-based safety requirement can be defined. The behavior of a glass structural member can be drawn as a line in the S, D, t-diagram. In this figure, the estimated behavior of a three layer heat strengthened PVB laminate glass beam is shown for different levels of damage: $D_{glass} = 0$; *two times* $0 < D_{glass} < 1$; $D_{glass} = 1$.

Especially the strength-time face of the diagram may show familiarity with load-displacement diagrams obtained from bending or tensile tests. However, those kinds of experiments simulate failure through overloading and coincide with a 100 % loss of structural glass section ($d = n$; $D_{glass} = 1$). Formulating safety requirements in terms of load-displacement would block the possibility to differentiate between different levels of damage. This is important because overloading is rarely the initiating cause of structural failure.

In Figure 4, an example of a minimum strength in the D,S,t-diagram is given by which the principle of the formulation of the consequence-based safety requirement is illustrated. However, in practice it will be hard to establish the complete three dimensional contours of such a space. Therefore, it is proposed to require the check of residual strength for a period of time at only a limited number of damage levels. The relevant damage, strength and time levels are introduced in the coming paragraphs. This will allow for more unified ways of testing and checking and also for a more easily readable, two dimensional presentation of the requirements as shown in Figure 5.

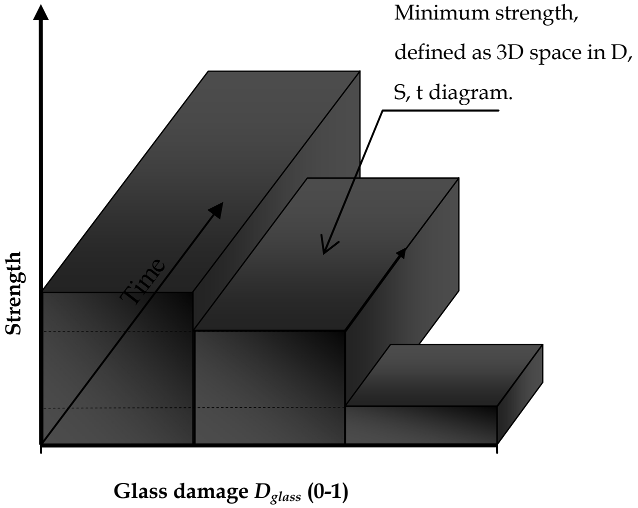

Figure 4: Example of a consequence-based safety requirement, formulated in terms of a minimum strength in the S, D, t-diagram

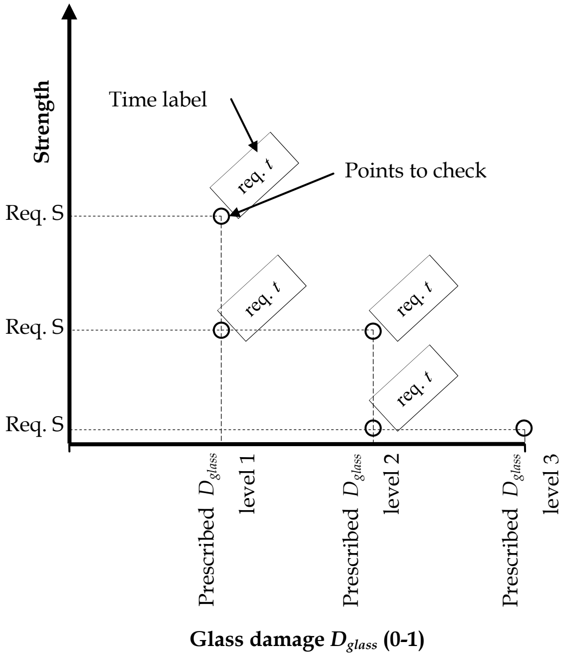

Figure 5: Example of how a consequence-based safety requirement might be represented two-dimensionally

5.2 *Axis demarcations: damage, strength, time*

5.2.1 *Damage (fig. 6)*

It is proposed to consider the following stages of damage:

- One outer layer broken, *d* = 1. Breakage of one layer is a relatively likely stage of damage, because of the susceptibility of glass to all kinds of failure causes. Because of its unprotected position, breakage of an outer layer is the most likely.
- All outer layers broken, *d* = *m*, with *m* = the number of outer layers. Although less likely than the breakage of one layer, all outer layers are more susceptible to sustaining all kinds of damage than the protected inner ones. Either accidental or purposeful (vandalism) mechanical damage may occur.
- All layers broken, *d* = *n*. The basis of a consequence-based approach is that this scenario should also taken into account. It may not be ignored just because it seems unlikely, although the post-failure strength requirements in such a case can vary from mild to severe depending on the application.

In a laminate with more than three layers, other damage levels may occur (e.g. three layers broken in a five layer laminate). However, these are not considered separately because it would result in an unnecessarily complex system and increasingly false accuracy.

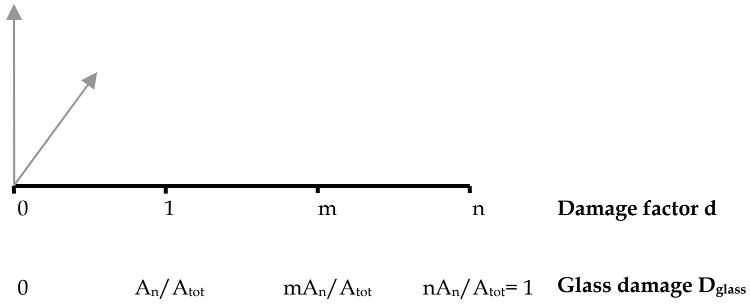

Figure 6: Relevant stages of damage to consider in a consequence-based approach

5.2.2 *Strength (Figure 7)*

Relating to action levels defined in the codes, several required levels of post-failure strength can be recognized. From low to high, they are:

- S_{sw}, Strength equal to the self weight of the member. A member with a strength below Ssw will collapse under its own weight.

- S_{apt}, Strength equal to the load at an arbitrary point in time. A member with strength below S_{apt} is likely to collapse under the load that will be exerted on the member at any given moment.
- S_{sls}, Strength equal to the serviceability limit state action, which is the representative maximum load during the reference life time.
- S_{uls}, Strength equal to the ultimate limit state action, which is the design maximum load during the reference life time.

To create redundancy on member level, failure should not coincide with collapse. This can be achieved by obtaining a ratio between collapse load and failure load equal to or greater than 1. A higher ratio indicates a larger redundancy. What value of this ratio is most appropriate for the approach presented here, can be debated. In [24] a ratio of 1.5 is suggested (for wood-glass composite beams), but not extensively argued. Experimental research on carbon fibre reinforced beams [19] resulted in post-failure strengths of 170 % of the initial failure strenght, while stainless steel reinforced glass beams have shown post-failure strengths of up to 140 % [22]. The author, however, suggests to require a ratio of at least 1.0. In combination with a duration requirement, this should be enough to avoid sudden collapse. Hence, the final demarcation on the strength axis is:

- $S_{rep,glass}$, Strength equal to the original nominal representative strength of the glass section. Note that, with a material partial factor greater than 1, the representative strength of the glass section ($S_{rep,glass}$) will always exceed the strength required for the ultimate limit state (S_{uls}), since $S_{uks} = S_s = S_{rep,glass}/\gamma_M$.

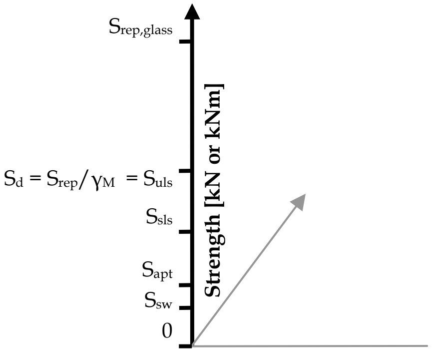

Figure 7: Relevant strength levels to formulate the post-failure strength requirement. The scale on the strength axis is approximate. The exact division will be dependent on the individual case. Strength is expressed in force (kN), moment (kNm) or even a combination of both, depending on the relevant way in which the member is loaded.

5.2.3 Time (Figure 8)

Few handholds were found to determine the duration at which the required strength levels should be maintained. The following provisional proposal is made:

- 0:00:30 hrs (30 s). Time necessary to immediately flee from a damaged structural member.
- 2:00 hrs. More extensive time to evacuate and close off a space surrounding a damaged member, as well as to remove the loads on the member.
- 24:00 hrs (1 day). Time to take structural measures (shoring).
- 72:00 hrs (3 days). Time to take extensive structural measures.
- Reference life time.

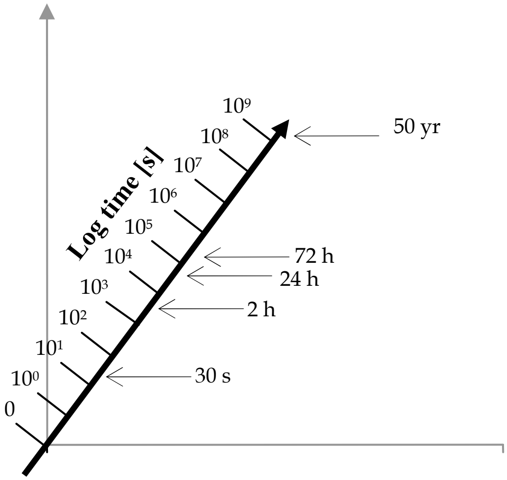

Figure 8: Relevant demarcations on the time-axis.

*5.3 **Member Consequence Classes***

With the above defined demarcations on the damage, strength and time axes, it is possible to define 3D spaces in the diagram. However, not all structural glass members will have to fulfil the same requirements. This is dependent on the consequences should a collapse occur, and thus on the function of the member in the structure as well as the function of the structure in general. Similar to the redundancy requirements stated in NEN-EN 1991-1-7, it is proposed to differentiate the requirements according to Consequence Classes (CC). To distinguish between the Consequence Classes in that code, which are formulated on the scale of the complete structure, and the ones proposed here, focusing on the scale of individual members, they are named 'Member Consequence Classes' (MCC). The consequence class of a member will be dependent on both the amount of likely direct personal injury (people getting hit by members, or falling because of member collapse), as well as the consequences for the structure (and thus indirect personal injury or economic loss) in case of failure. For each consequence class, a different prohibited space in the D, S, t-diagram is formulated.

The likelihood of direct personal injury is dependent on the type and accessibility of the building in which the glass member is applied. Here it is proposed to distinguish between private, semi-public/office and publicly accessible structures. The consequences for the structure of which the glass member is part, are dependent on the role of the part within that structure. Distinction is made between key members (according to NEN-EN 1991-1-7), primary members and secondary members. In practice, it may be hard to determine if a member is 'key', 'primary' or 'secondary'. Definite descriptions of these concepts are not proposed yet, but tentative descriptions and examples are given in table 3.

Table 3: The role of a member in a structure

Role	**Tentative description**	**Examples**
Key	According to [7]: A structural member upon which the stability of the remainder of the structure depends.	
Primary	Member that carries other members of the main load bearing structure and/or floors.	Columns, floor beams, roof beams carrying secondary beams.
Secondary	Member that carries no parts of the main load bearing structure or floors.	Roof beams, fins.

Together, nine combinations of building type and member role can be made. For each, a different MCC could be defined. However, when considering what requirements are desirable for those possible combinations, the defined number of MCCs was limited to six (Table 4). Nonetheless, the three-dimensional diagram formulation of the consequence-based failure requirement provides ample opportunity to create more (sub)classes. It thus allows further diversifying requirements for specific structural applications, should this be deemed desirable. Such fine tuning however, falls outside the scope of this paper.

The members in most existing glass structures can be categorized as MCC1, MCC2 or MCC3; on the other hand, MCC4, MCC5 and MCC6 members, have hardly been realized. It is part of the objective of the explicit safety formulation here presented to provide a theoretical safety framework for more extensive glass structures. It provides a clear goal to which such structures should be designed.

Table 4: Member Consequence Classes for combinations of building type and member role

Consequence of collapse		
Loss of function of the structure	**Likely amount of direct personal injury**	
Depends on role of member in structure	**Depends on accessibility**	**MCC**
Key member	High – Public	6
Key member	Medium – Semi-public/office	6
Key member	Low – Private	5
Primary member	High – Public	4
Primary member	Medium – Semi-public/office	3
Primary member	Low – Private	2
Secondary member	High – Public	3
Secondary member	Medium – Semi-public/office	2
Secondary member	Low – Private	1

Table 5: Numerical formulation of the proposed post-failure requirements for each of the six Member Consequence Classes

MCC	Required strength and period of time for certain amount of damage (number of broken layers)							
	$d < 1$ (pre-failure)		$d = 1$ (outer)		$d = m$ (all outer)		$d = n$ (all)	
	Strength	time	Strength	time	Strength	time	Strength	time
1	S_{uls}	t_{ref}	S_{uls}	2:00 h	S_{apt}	> 30 s	0*	0*
			S_{sls}	24:00 h				
2	S_{uls}	t_{ref}	S_{uls}	24:00 h	S_{uls}	2:00 h	S_{apt}	> 30 s
			S_{sls}	72:00 h	S_{sls}	24:00 h		
3	S_{uls}	t_{ref}	S_{uls}	72:00 h	S_{uls}	24:00 h	S_{apt}	2:00 h
					S_{sls}	72:00 h		
4	S_{uls}	t_{ref}	S_{uls}	t_{ref}**	S_{uls}	72:00 h	S_{sls}	24:00 h
					S_{sls}	t_{ref}	S_{apt}	72:00 h
5	S_{uls}	t_{ref}	S_{uls}	t_{ref}	S_{uls}	t_{ref}	S_{uls}	24:00 h
							S_{sls}	72:00 h
6	S_{uls}	t_{ref}	$S_{rep,glass}$	t_{ref}	$S_{rep,glass}$	t_{ref}	$S_{rep,glass}$	t_{ref}

** If $n = m$, than the requirement for $d = m$ still applies.*

*** t_{ref} = reference life time.*

5.4 *Minimum post-failure strengths*

Now that six Member Consequence Classes have been defined, different requirements can be formulated for each class. The requirements are numerically listed in table 5. They are visually presented in the D, S, t-diagram in figures 10 through 15. It is generally required that the member in question is not hidden (which is actually unlikely in a glass structure), i.e. that a failure can actually be observed.

To obtain safety, it is important that a degree of post-failure strength is guaranteed. However, it is important to realize that the post-failure strength does not necessarily have to be provided by the structural member in question. If the structure provides alternative load paths that can carry the loads required for a certain Member Consequence Class, then the member can be classified in that Class even though it does not provide the required post-failure strength itself.

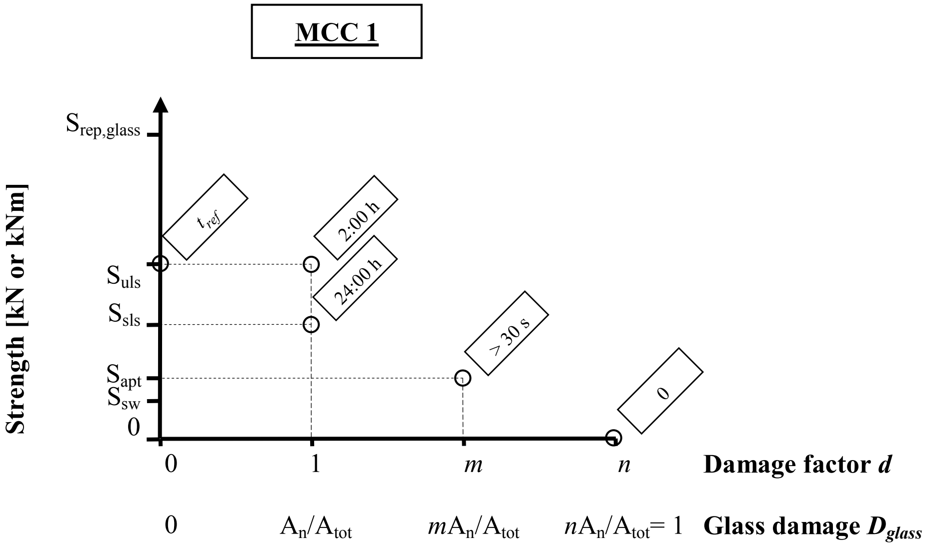

Figure 9: Consequence-based safety requirement for MCC 1. Only in case of one layer breaking should there be significant post-failure strength. In that case the initial requirement is S_{uls} for a short period of time, followed by a bit longer requirement of S_{sls}. The initially rather high strength requirement is based on the fact that defects are more likely to get crucial just at the moment a high load (uls) is exerted. Because this MCC only applies to secondary structural applications in private buildings, just enough time to flee from the failed structural member is deemed enough in the case of two layers breaking. If more than two layers are used, no residual strength is required when all glass layers break (D_{glass} = 1).

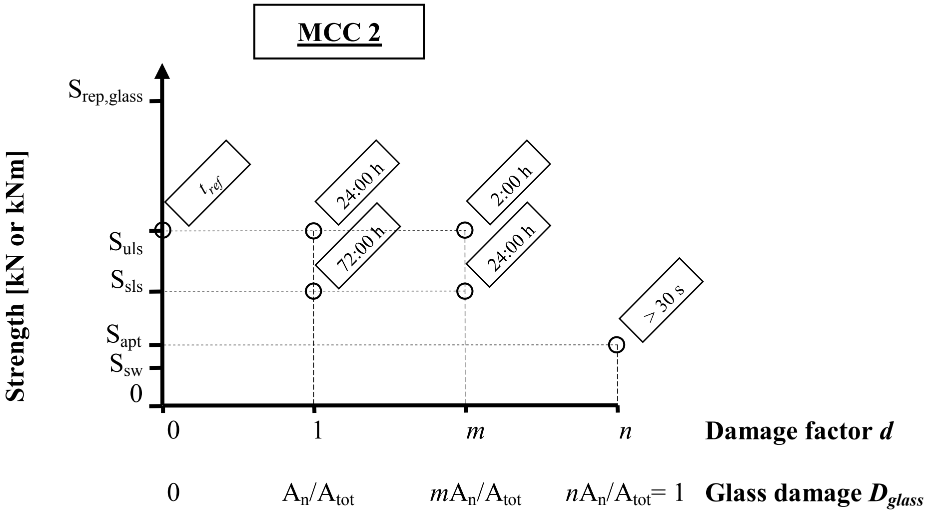

Figure 10: Consequence-based safety requirement for MCC 2. The primary difference of this MCC with the previous one, is that it is required to maintain significant post-failure strength after the outer layers of the member are broken. Because MCC 2 members may be used in semi-public buildings, the chances of both accidental and purposeful (vandalism) damage increase and collapse should not occur (quickly). The uls-requirement is for two hours, usually enough to decrease the load or evacuate the relevant area.

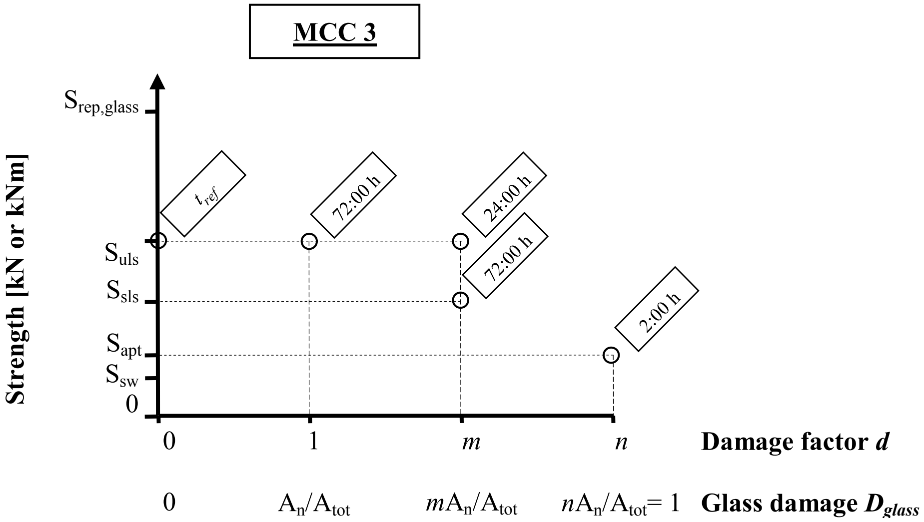

Figure 11: Consequence-based safety requirement for MCC 3. Because members of this class can be applied in publicly accessible space or for primary members in semi-public spaces, quick collapse is unacceptable at a random moment even in case all glass layers break. If that would occur, the action at an arbitrary point in time should be carried for at least two hours, which should be enough to evacuate the relevant area and remove loading on the member.

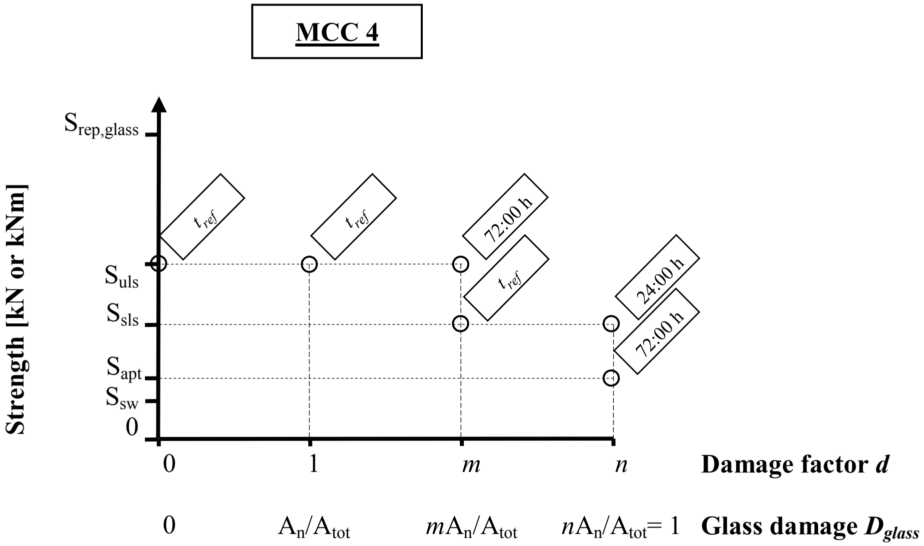

Figure 12: Consequence-based safety requirement for MCC 4. In case of MCC 4, the post-failure strength requirement after breakage of the complete section is increased to the serviceability limit state, thus making sudden collapse unlikely at any moment (as opposed to a random moment as with MCC 3).

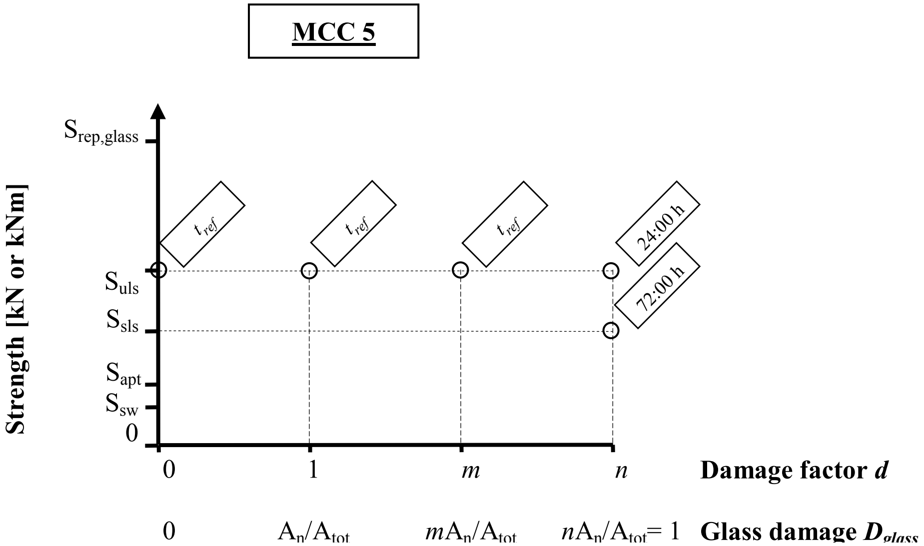

Figure 13: Consequence-based safety requirement for MCC 5. Because of the structural importance of MCC 5 members (key), they are required to be able to carry the ultimate limit state load for a significant amount of time load even in case of breakage of the complete glass section. This will not only allow for evacuation and closing of the premises, but also for load removal and structural measures thus increasing the probability that the structure will survive.

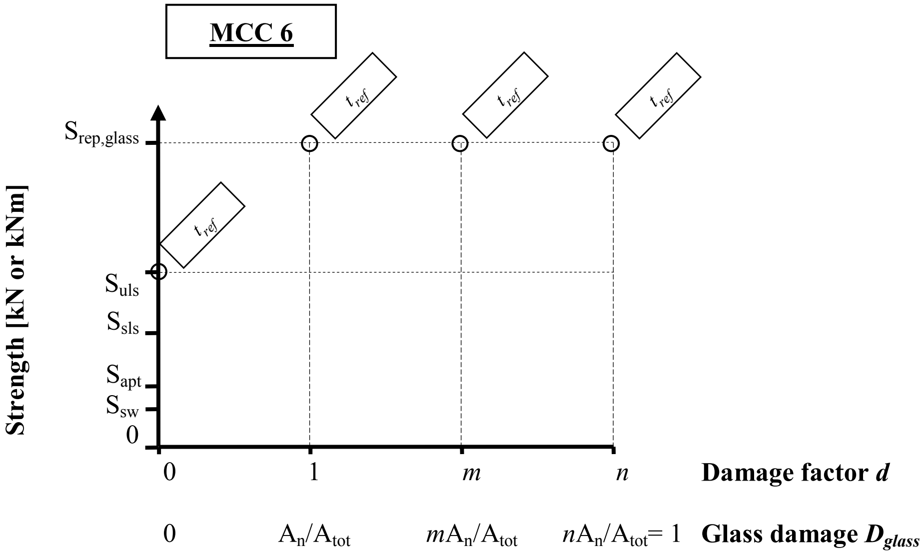

Figure 14: Consequence-based safety requirement for MCC 6. These members not only play a vital role in the structure, but are also applied in commonly accessible buildings likely to contain many people at a given moment. Therefore, their behavior should be inherently safe (comparable to steel), independent on the loading it was calculated for. Thus, they are required to have a post-failure strength at least equal to their pre-failure strength.

6 Conclusions

Contemporary structural glass codes focuses primarily on the probability of the risk of failure. Consequence-based requirements (if any) are formulated very generally and concisely. Although the Eurocodes provide more extensive guidance on a consequence-based approach, those are solely aimed at the level of the complete structure, rather than that of individual members. This is caused by the fact that common structural materials possess inherent redundancy through their material behavior. Glass lacks this redundant material behavior and is sensitive to numerous failure causes. This is well known and it is reckoned with in structural glass projects. It is therefore surprising that formulating consequence-based requirements for structural glass members is not discussed in general terms in literature concerning structural glass. Measures taken to prevent sudden collapse are only described in relation to specific projects and the solutions there applied.

Therefore, the author has proposed to add a consequence-based approach to the existing probabilistic methods. Combined, these approaches make it possible to formulate a priori the level of safety that is desired and to objectively evaluate and compare design alternatives for a specific application.

The consequence-based approach formulates requirements in terms of residual strength for a certain period of time, at prescribed levels of damage. The damage levels are quantified as the number of broken glass layers. The concept of Member Consequence Classes (MCC) has been introduced, in order to be able to differentiate requirements for members based on their role within a structure and the function and accessibility of the structure at hand. The consequence-based approach does not exclude any type of structure or structural member, and thus sets an objective in terms of post-failure behavior to develop structural glass members that can be applied in *any* structure.

The proposed formulation of consequence-based safety requirements makes it possible to develop standard structural glass members for specific applications, based on standardized testing sequences which – by virtue of their standardized nature – can be much more extensive than the usual safety testing of structural glass members.

The presented method is novel, and thus still requires elaboration. The practicability of the method will be investigated by assessing imaginary structures and existing projects. Future research will also aim at developing the proposed concept to also include joints, as well as evaluating the chosen axes demarcations and (requirements to) the Member Consequence Classes. Furthermore, temperature requirements may be added to the presented system. The author would welcome any remarks or suggestions to further develop the proposed approach.

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