Tensile behaviour of soda-lime-silica glass and the significance of load duration – A literature review

Meyland, Martin Jensen; Nielsen, Jens H.; Kocer, Cenk

Published in: Journal of Building Engineering

Link to article, DOI: 10.1016/j.jobe.2021.102966

Publication date: 2021

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Meyland, M. J., Nielsen, J. H., & Kocer, C. (2021). Tensile behaviour of soda-lime-silica glass and the significance of load duration – A literature review. Journal of Building Engineering, 44, [102966]. https://doi.org/10.1016/j.jobe.2021.102966
Tensile behaviour of soda-lime-silica glass and the significance of load duration – A literature review

Martin J. Meyland, Jens H. Nielsen, Cenk Kocer

Keywords: Soda-lime-silica glass, time-dependent strength, static fatigue, dynamic fatigue, loading rate, experimental material characterisation

Abstract

Soda-lime-silica glass is a widely used material in society today and its strength over various loading times is of major engineering concern. This paper reviews studies from the published literature, which report on the time-dependent tensile behaviour of soda-lime-silica glass. Furthermore, current normative definitions are reviewed and compared to the literature concerned with time-dependent glass strength.

In general, there exists two common applied test methods to characterise glass: (1) the static fatigue test, a constant applied stress over time, and (2) the dynamic fatigue test, a constant applied stress rate. After a thorough search of the available scientific and engineering publications, 92 articles were found to have studied glass using these two test methods. In the tests the typical setups employed to apply load on a glass specimen were the three-point and four-point-bending, and axisymmetric bending configurations. From these tests the load duration and loading rate effects on the strength of glass were investigated. For comparison purposes, all data found were normalised with respect to a reference strength, which for static fatigue is a '60-second' strength, and for dynamic fatigue is a strength corresponding to a stress rate of 2.0 MPa s⁻¹. This means that the time-dependent effect on strength are highlighted and the governing crack properties and size effects are not included.

The review supports the general observations that the tensile strength of soda-lime-silica glass is strongly affected by the load duration. The static fatigue tests generally show that strength decreases with increasing load duration. Furthermore, the dynamic fatigue tests show that glass strength increases with loading rate, equivalent to a decreasing load duration. However, a significant lack of data is present at the very short and long loading times, making it difficult to draw a final conclusion at the extreme ends of the load duration and loading rate tests. Additionally, the experiments demonstrate that glass tested in air is less susceptible to static and dynamic fatigue as compared to water immersion, or in air at high relative humidity. However, for the Young's modulus, there are a limited number of studies in the literature and these studies do not highlight a conclusive outcome regarding the sensitivity on loading rates. The fatigue data also support well the load duration dependence given in the various Standards for the design of glass structures, with a few exceptions.

1. Introduction

In civilian infrastructure, soda-lime-silica glass is used in a wide range of applications, such as windshields, load-bearing glass beams, residential windows, large glass plates covering whole building facades, and many more. To ensure improved performance, these applications are typically based on post-processed flat glass (also denoted 'float' or 'annealed' glass) either in the form of laminated glass, tempered glass, or a combination of both. Depending on the application, the glass is exposed to different load history during its lifetime, which can be a period of stress as long as several years to as low as a few microseconds. Therefore, it is important that a detailed level of knowledge about the material dependent constitutive relation and the failure criteria has been developed over a wide range of strain rates (see Fig. 1). This is essential for the design of glass structures that will have a well-defined service lifetime.

Examples of the typical long/short term loads found to act on glass structures are, snow loads [1-4], wind loads [5-11], seismic loads [12-18], wind-born debris impact [19-24], ballistic (hail and bullets) impact [25-31], and blast loads (accidental and man-made) [32-58].

https://doi.org/10.1016/j.jobe.2021.102966
Received 14 February 2021; Received in revised form 2 July 2021; Accepted 8 July 2021
Available online 22 July 2021
2352-7102/© 2021 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
all cases, the load duration as well as the rate of loading affects the static and dynamic glass strength significantly. The rate-of-loading effect also impacts other structural materials used by civil engineers, see e.g. Refs. [59–61]. Nevertheless, the affect on strength is only significant when the duration or rate-of-loading changes by more than one order of magnitude.

In the past, research on glass strength focused on long-term behaviour (static to quasi-static loading) and the effects of sub-critical crack growth (described in Sec. 2), showing that the strength of glass is being sensitive to the applied load duration. Even though glass is generally acknowledged to exhibit a higher dynamic strength, the available data, however, is quite limited for higher loading rates relevant to impact and blast loading events [49, 53, 55, 62, 63]. In general, this is attributed to the fact that dynamic load experiments are much more complicated to perform and interpret, because several parameters such as the measurement equipment, specimen geometry, and stress-wave propagation effects, must be given careful consideration.

To provide a broad overview of the time-dependent tensile behaviour of soda-lime-silica glass, it is the aim of this paper to review all available literature (to the best of the authors’ knowledge) concerning experimental investigations on the mechanical material properties, such as strength and stiffness, over a wide range of load duration and rate of loading. No limits are set on the magnitude of the load duration and rate of loading to be considered. Furthermore a brief overview of applied experimental techniques is presented. In closing, a direct comparison is made between the collected strength data and various available Standards defining the load duration dependence on glass strength.

2. Fundamental aspects of time- and rate-dependent failure

Typically, glass is a linear elastic, isotropic material that exhibits brittle failure. Before post-processing, such as chemical treatments or thermal/chemical tempering, glass strength is essentially governed by the surface flaws (or surface cracks) located on the tensile loaded surface. The compressive strength of glass is much higher, and usually not important in structural applications; therefore, not considered in this paper. As with many other brittle materials, glass will fail instantaneously after reaching a critical value for the stress intensity at the tip of one surface crack. However, because of the characteristic differences in surface flaws, glass strength is not considered to be a material constant, and the size of the glass element, the load history (intensity and duration), the residual stress, and the environmental conditions, also affect significantly the ultimate strength exhibited. Moreover, glass has a unique characteristic where its atomic structure reacts with moisture from the environment [64–66]. As a result, sub-critical crack growth\(^1\) effects are observed under normal environmental conditions where a level of humidity is present and surface flaws grow under a constant tensile load (see e.g. Refs. [67–69]). This is directly related to the phenomenon of long-term loads leading to a distinct reduction in strength. The first observation of static fatigue was published in 1899 by the French scientist Grenet [70], who also explained the unexpected fracture of filled champagne bottles by the delayed failure of glass\(^2\).

Taking into account the effect of load duration on glass strength requires a known corrosive crack behaviour, characterised through the crack velocity, \(v\), and the stress intensity factor for mode I loading, \(K_I\). Extensive studies have looked at the effect of different environmental conditions [72–84], and within the construction industry water appears to be decisive. A schematic representation of the relationship between \(v\) and \(K_I\) is given in Fig. 2 with four essential regions highlighted:

0 In region 0, no measurable sub-critical crack growth effects occur below \(K_{Ic}\). For soda-lime-silica glass this value can range from 0.14 to 0.28 MPa m\(^{1/2}\) in water [79, 83, 85–90] and from 0.37 to 0.39 MPa m\(^{1/2}\) in air (50% RH) [86, 88], at crack velocities as low as \(10^{-14}\) m/s.

I In region I, the crack velocity is essentially governed by the molecular mechanisms of stress corrosion at the crack tip. The crack growth rate thus depends on the applied stress intensity and relative humidity. A measure of how reactive water molecules are within the glass lattice, is characterised by the slope of the curve. For region I, the fracture behaviour in water at 25 °C can be characterised with a minimum crack velocity of around \(10^{-10}\) m/s [74]. While in very dry air (0.017% RH) a maximum crack velocity of \(10^{-7}\) m/s is observed, the maximum crack velocity in saturated air (100% RH) increases to \(10^{-4}\) m/s [73].

II In region II, sub-critical crack growth is still influenced by the chemical reactivity of the surrounding environment, but is independent of the stress intensity. As the crack velocity is directly proportional to relative humidity, a plateau is formed in the \(v(K_I)\) curve. The constant crack velocity range narrows as relative hu-

\(K_{Ic}\) = the stress intensity factor for mode I loading, \(v\) = crack velocity, \(K_I\) = stress intensity factor.

\(K_{Ic}\) = the stress intensity factor for mode I loading.

---

\(^1\) Other terms are used as well, such as ‘slow crack growth’, ‘delayed failure’, ‘static fatigue’, and ‘environmental fatigue’. The term ‘stress corrosion’ mostly refers to the chemical process.

\(^2\) Partial English translation provided by Preston [71].
humidity increases, which emerges from the findings of Wiederhorn [73].

III In region III, the $v(K_i)$-curve increases rapidly approaching the limit for an inert environment. At this point, it is no longer possible for the surrounding reactive environment to follow the crack tip, thus resulting in an environment independent crack velocity between $10^{-3}$ m/s and 1 m/s. After reaching the fracture toughness of the glass, $K_{ic}$, crack growth becomes unstable leading to failure of the glass element. For soda-lime-silica glass $K_{ic}$ is estimated to be between 0.72 and 0.82 MPa m$^{1/2}$ at room temperature [91].

In general, the determination of the design lifetime of a glass element is based on region I, while the contribution from region II and III can be neglected for quasi-static loads. A good approximation of sub-critical crack growth in region I is described by the following empirical power law originally proposed by Evans and Wiederhorn [92]:

$$v = \frac{da}{dt} = v_0 \left(\frac{K_i}{K_{ic}}\right)^n$$

(1)

where $v_0$, on a logarithmic scale, represents the ordinate of $K_{ic}$ and the exponent $n$ defines the slope of the curve. When the value of the crack growth parameter $n$ is high, it indicates that the chemical reactivity at the crack tip is reduced due to a decrease in humidity, resulting in slower crack growth. The opposite is true when $n$ is low. The well-established theory of linear elastic fracture mechanics (LEFM) defines the stress intensity factor, $K_i$, with respect to a geometry (correction) factor $Y$ (0.637 for half penny shaped cracks and 1.12 for edge cracks in semi-infinite plates) and a crack (or flaw) depth, $a$ (see e.g. Ref. [93]):

$$K_i = \sigma Y \sqrt{a}$$

(2)

where $\sigma$ is the stress acting normal to the crack plane. Inserting Eq. (2) into Eq. (1) and assuming the ordinary differential equation to be valid over the full range of $K_i$ with a constant $n$, the method of variable separation yields:

$$\int_{t_0}^{t} \sigma^n(t) \, dt = \frac{2K_{ic}^n}{(n-2)a_0^{n-3/2}v_0(Y\sqrt{a})^{n-1/2}}$$

(3)

With a given stress history, $\sigma(t)$, and neglecting the crack growth threshold, $K_{th}$, this equation can be used to estimate the time-to-failure of a crack (or flaw) with an initial depth, $a_0$.

### 2.1. Crack resistance at constant stress

For a constant applied stress, i.e. $\sigma(t) = \sigma_{fs}$, as shown in Fig. 3a, a static crack resistance for any given load duration is found by inserting the stress history into Eq. (3):

$$\sigma_{fs} = \alpha a_0^{-1/n}$$

(4)

where

$$\alpha = \left[\frac{(n-2)a_0^{n-3/2}v_0(Y\sqrt{a})^{n-1/2}}{2K_{ic}^n}\right]^{1/n}$$

with $t_{fs}$ being the time to failure or lifetime of a given initial crack exposed to $\sigma_{fs}$.

It follows from Eq. (4) that for two identical cracks ($a_0$, $Y$) found on two identically sized glass elements, index 1 and 2, for identical conditions ($v_0$, $n$, $K_{ic}$), the interrelationship between the constant applied stresses and lifetimes can be expressed as:

$$\sigma_{fsj} = \left(\frac{t_{fsj}}{t_{fs1}}\right)^{1/n}$$

(5)

This result can be used to determine $n$, since it is independent of $v_0$.

#### 2.2. Crack resistance at constant stress rate

In the case of a constant stress rate, $\dot{\sigma}$, commonly used for strength testing glass, the applied stress increases linearly with time as illustrated in Fig. 3b:

$$\frac{d\sigma}{dt} = \text{const.} \Rightarrow \sigma(t) = \sigma_0 + \dot{\sigma}t$$

(6)

Similar to $\sigma_{fs}$, a dynamic crack resistance, $\sigma_{fsd}$, can then be found by inserting Eq. (6) into Eq. (3):

$$\sigma_{fsd} = \beta \dot{\sigma}^{1/(n+1)}$$

(7)

where

$$\beta = \frac{\sigma}{\sigma_{fsd}} = \frac{\sigma_0 + \dot{\sigma}t}{\sigma_{fsd}}$$

Here, the constant $\beta$ is defined such that it depends on $\sigma$ from tests with constant applied stress (see Eq. (4)). By doing so, one could use data from constant stress rate tests to describe crack growth in cases with constant applied stresses. The reverse approach is also possible when data from tests with constant applied stresses is available and an estimate of crack growth at constant stress rate is needed. However, both approaches imply that cracks and conditions must be identical to be able to perform the conversion.

The use of Eq. (7) was first suggested by Charles in 1958 [94] to describe rate dependent crack growth at constant temperature in his dynamic load experiments on glass. For low stress rates, it is sufficient to
only consider the contribution from region I. However, for dynamic events over short times, such as impact loads and blast waves, region II and III seem to affect the design lifetime significantly according to Kuntsche [95].

Also, Eq. (7) can be used to describe the interrelationship dependence between two identical cracks (a0, Y) found on two identically sized glass elements, index 1 and 2, in identical conditions (v0, n, Kic) loaded at constant stress rates \( \dot{\sigma}_1 \) and \( \dot{\sigma}_2 \):

\[
\frac{\sigma_{f,2}}{\sigma_{f,1}} = \left( \frac{\dot{\sigma}_2}{\dot{\sigma}_1} \right)^{1/(n+1)}
\]  

(8)

Since Eq. (8) also is independent of \( v_0 \), it is commonly used to determine \( n \) from experiments, by plotting the failure stress as a function of the stress rate on a logarithmic scale, resulting in a slope of \( 1/(n + 1) \). However, this is only valid in limited cases in which flaws, conditions, and \( v_0 \) are identical during all tests. According to Haldimann et al. [96], \( v_0 \) can be strongly stress rate dependent, which is why this method should be used with caution.

It has been shown that the \( \nu(K) \)-curves, as illustrated in Fig. 2, successfully describe the variations observed in time-to-failure at constant applied tensile stress. Expanding on this, these curves can be used to examine the characteristics of dynamic failure at a constant stress rate; this was first reported by Evans in 1974 [85] and later reexamined by Evans and Johnson [97] and Chandan et al. [98]. These authors suggest that by integrating over the 4-regions of the sub-critical crack growth velocity curve, a new curve is obtained where fracture strength is a function of stress rate (the corresponding four regions are now A, B, B’ and C), as depicted in Fig. 4.

At low stress rates, region A, glass strength begins to increase from a minimum value, \( \sigma_0 \). For an increasing stress rate, region B, there exists a simple logarithmic relationship between \( \sigma_f \) and \( \dot{\sigma} \), which is identical to that derived by Charles [94] (see Eq. (7)). At still higher stress rates, region B’, strength varies in a non-trivial manner with stress rate. Lastly, at the highest stress rate, region C, strength is independent of stress rate due to the absence of sub-critical crack growth effects.

Evans and Johnson [97] described the transition between the different regions analytically and presented strength data at stress rates ranging from \( 2 \cdot 10^{-4} \) to \( 3 \cdot 10^4 \) MPa s\(^{-1}\). However, their results did not provide any conclusive evidence of distinctly different regions. A few years later, Chandan et al. expanded on this work to try and characterise the two higher regions, B’ and C, using stress rates between \( 5 \cdot 10^{-1} \) and \( 2 \cdot 10^5 \) MPa s\(^{-1}\). However, the work was unsuccessful because the measured strength data would fit region B only and no evidence was found of the two higher regions, confirming the general agreement on the applicability of Eq. (7).

As shown, the fracture resistance of glass, for a surface crack (or flaw) loaded at either constant stress or constant stress rate, can in both cases be described by an empirical power law, in which the stress intensity at the crack tip is given by LEM. In either load case, the load duration, or time to failure, is a fundamental parameter governing the fracture resistance of a glass element. For constant applied loads, the load duration is a common measure when investigating material characteristics, whereas it is the rate of loading that is of more importance when considering a constant loading rate. However, the constant loading rate is inversely proportional to the load duration, allowing a direct comparison between these two types of load configurations. In the following sections present, and discuss, the study undertaken to understand better the behaviour of soda-lime-silica glass to tensile loads, using the two load configurations. First, the focus of this work is on the various applied experimental techniques, followed by a discussion of the material characteristics measured.

3. Experimental techniques

A variety of experimental techniques have been employed by researchers to investigate the mechanical properties of glass for various load conditions, using strain rates typically expected in practice. The typical strain rates found in engineering applications, range from creep loading \( (< 10^{-6} \text{ s}^{-1}) \), through the quasi-static case of around \( 10^{-6} \text{ s}^{-1} \), \( 10^{-2} \text{ s}^{-1} \) to an intermediate range \( (\approx 10^{-4} \text{ s}^{-1} - 1 \text{ s}^{-1}) \) covering structural dynamics imposed by wind and seismic loading, to even higher levels \( (> 1 \text{ s}^{-1}) \) that include debris impact and blast loads, as shown in Fig. 1. Other relevant load conditions that have been used are constant loads, e. g. similar to snow load or dead-weight, also considered as static loads, where strength is dependent on load duration, rather than the loading rate.

In general, two different test methods can be identified, which are used to study the mechanical properties of glass:

1. **Static fatigue test** \( (\sigma = \text{const.}) \) – used to investigate failure that would occur over time when a constant stress is applied, see Fig. 3a. This method is used to measure the sub-critical crack growth effects that result in delayed fracture. The advantage of such tests is that the test conditions are representative of typical scenarios of long-term loading. However, a disadvantage is that they can be extremely time-consuming.

2. **Dynamic fatigue test** \( (\dot{\sigma} = \text{const.}) \) – used to investigate fracture that would occur at a constant stress/strain rate, see Fig. 3b. This is a common method used to investigate the rate-dependent tensile strength, and often used to identify the crack growth parameter, \( n \), using Eq. (8).

Tensile strength is a critical parameter when designing load carrying glass structures. To study it by means of the above mentioned methods, several experimental setups have been employed to test materials on an engineering scale; the most common are the three-point and four-point bend test, and the axisymmetric bending (coaxial double ring tests). The load configurations and resulting stress distributions are illustrated in Fig. 5.

However, other, albeit rather rare techniques have also been reported, such as uniaxial tension and diametral compression tests. For the direct investigation of sub-critical crack growth effects in glass, the double cantilever beam test is a widely used technique. A brief introduction to each technique is provided below. Local characterisation of a
material can also be carried out by e.g. indentation techniques such as the Vickers indentation; however, these methods are not within the scope of this review paper.

**Three-point bending:** The glass sample is loaded at three points as shown in Fig. 5a. The load points are typically placed symmetrically over the test sample. In order to minimise membrane stresses, two of the applied forces (typically the reaction points) are roller contacts, allowing for horizontal movement. The setup introduces a linearly varying tensile stress on the bottom surface between the two roller supports, with a maximum value below the central load point, as shown in Fig. 5a. In this configuration, the probability of finding a critical favourably located flaw, in the relatively small area of highest tensile stress, is low. It is, therefore, important to locate the origin of fracture in order to precisely determine the strength of the test sample. Furthermore, the distribution of stress can complicate the statistical analysis of the data.

**Four-point bending:** This configuration is similar to the previous test with the difference that there are four contact points as shown in Fig. 5b. Again the contact points are typically placed symmetrically and three of the applied forces are rolling contacts (free horizontal movement) in order to minimise membrane stresses. An advantage over the three-point bend test is the relatively larger area of maximum tensile stress as shown in Fig. 5b. However, both the three- and four-point bend tests produce undesirable high tensile stresses at the sample edges. Since there is a higher probability of finding a critical favourable flaw at the edge of the sample as compared to surface areas far from the edge (a consequence of glass cutting and handling), it can be challenging to determine the true surface strength of the glass specimen using these two bend test methods.

**Axisymmetric bending:** In order to minimise undesirable edge effects, the axisymmetric bend configuration can be employed. Such tests are usually carried out in a ring-on-ring test setup where two concentric rings sandwich a flat sample: a support ring on which a sample of glass is placed and then loaded using a smaller load ring. The circular geometry gives rise to rotationally symmetric stresses, where the maximum surface stress is nearly uniformly distributed within the area of the load ring. This is similar to the four-point bend test, but with the exception that this configuration reduces significantly the stress at the specimen edges, resulting in strength data directly related to the surface, see Fig. 5c. However, due to non-linear effects, the acceptable specimen size in the test is limited; to overcome the limit more complicated test setups have been suggested as in EN 1288-2 [99].

**Other loading techniques:** Although it is often more convenient to test glass in bending due to the relatively simple support and load configuration, some researchers have used alternative techniques to study the tensile behaviour of glass. One of them is the uniaxial tensile test, which is a direct and fundamental technique used to characterise the pure tensile behaviour of a solid. However, for the test the tensile grips to the sample must be chosen carefully since large stress concentrations at the grip point would be highly undesirable. This may explain the infrequent reporting of direct tensile tests. There is also the diametral compression test. It is used for indirect measurements of the tensile strength of brittle materials, such as rock like materials and concrete. By placing a cylindrical specimen in diametral compression, as shown in Fig. 6, a broad region of tensile stress is produced, with a narrow region of compressive stress produced at the ends of the sample, where the load is applied. The maximum tensile stress is located at the centre of the sample. Unfortunately, this method tends to overestimate tensile strength [100], and together with a load configuration that is far from the typical bending induced tensile stresses, it explains why this method is seldom used. Another, frequently reported test is the double cantilever beam technique (DCB). However, its intention is not to determine the strength of a material, but rather to characterise crack growth in the pure mode I opening configuration. By applying a constant tensile load...
perpendicular to a crack surface of known dimensions, in a predefined sample geometry (see Fig. 8), the crack velocity is measured where the stress intensity at the crack tip can be calculated for any measurable length of the crack. There are several other methods used to measure stable and unstable crack growth data over quite a wide range of crack velocities. In this paper the reviewed articles have only used the DCB method and as such it is the only method presented.

The discussion above provides a brief outline of the more common load configurations. It is, however, more complete to also consider the implications of how the load is actually applied to a glass specimen; that is, what are the implications of static and dynamic loads.

3.1. Static fatigue tests

In general, static fatigue data is gathered by measuring the time-to-failure of a number of samples at different constant applied stresses, as shown in Fig. 3a. A summary of the failure times achieved in the published works is shown in Fig. 7, while the detail of a review of the tests can be found in Appendix A, Table A.1.

It is relatively straightforward to implement a test on glass using a constant load configuration. Grenet [70] in 1899 was one of the first to report performing such a load test. He used a bucket filled with water, hung from the centre of a glass plate, which was supported along two of its four edges (three-point bending), to study time-dependent failure. Since then, the use of ‘dead-weight’ loads has been extensive; in most cases, the weight is applied by either filling containers with e.g. sand [103] or weights, attached to a lever arm that applies the load to a specimen in a three- or four-point bend test configuration [104–109].

This simple static configuration allows users to perform measurements over weeks to months (see e.g. Ref. [110]). However, failure over shorter periods is only possible for much higher loads. Typically, this then produces undesirable inertial effects, which places a lower limit on the static load duration. This explains why the majority of published data summarised in Fig. 7 are at failure times above 1 s. Baker and Preston [103] and, Mould and Southwick [105] have both reported measurements below this limit using an apparatus constructed from a loudspeaker, which is capable of applying loads without inertia effects. Thereby reaching static fatigue failure times as low as approx. 2.5 ms.

Even though ‘dead-weight’ load configurations have proven to be highly useful, since the 1980s a new class of ‘universal testing machines’ have been developed. Using integrated systems with efficient mechanical actuators and computer software, these testing machines have greatly improved the study of the static fatigue process [111–114]. This allowed highly controllable load duration in the range of 4 s to almost 1 d.

3.1.1. Crack velocity measurements

Since it is common practice to measure crack velocities at constant applied load, the study of crack growth can be considered as a subgroup of static fatigue tests. Therefore it is included in this review. From the literature reviewed here, it is found that the double cantilever beam technique is employed in most work. In this technique a glass specimen with an initial edge crack of known dimensions is prepared and loaded at constant load perpendicular to the crack surfaces, as shown in Fig. 8. In this specimen/load configuration the stress intensity of the crack is well defined, Eq. (2), and therefore, can be calculated at each point the velocity of the crack is measured, resulting in a $v(KI)$-curve and an estimate of the sub-critical crack growth parameters, $KIC$, $V0$, and $n$, defined in Eq. (1) (also see Fig. 2).

![Fig. 7. The failure times reported in the published static fatigue tests. See also Table A.1.](image-url)
3.1.2. Definition of relative applied stress

The static fatigue data of soda-lime-silica glass reviewed here are reported for failure loads presented as either an applied mass (lb or kg) or an applied stress (psi or MPa). In the following assessment and discussion, all reviewed data are converted to a relative applied stress by normalising with respect to a ‘60-second’ strength, \( \sigma_0 (t_0 = 60\ s) \), using the relationship defined in Eq. (5). Therefore, the crack growth constant \( \alpha \) vanishes, and only the relative glass strength is highlighted, without showing absolute strength values for the various specimen sizes provided in Table A.1.

3.2. Dynamic fatigue tests

All the reported dynamic fatigue data are measurements of the failure load of a number of samples at different constant loading rates. The detail of the experiments in these previous tests are given in Appendix A, Table A.2, while Fig. 9 is a summary of the range of loading rates achieved, which also indicates the strain rates that can be expected for the different experimental techniques. However, it should be noted that the strain rate not only depends on the experimental technique but also on the specimen geometry under investigation.

Typically, universal testing machines are used to strength test glass in the quasi-static load regime at constant stress rates near 2 MPa s\(^{-1}\) (see e.g. Refs. [99,115,116]), corresponding to strain rates of around 1 × 10\(^{-5}\) s\(^{-1}\). An air chamber on one side of the constrained glass pane was pressurised with explosive charges (black powder) placed inside a box, to which a glass pane of size 355.6 × 482.6 × 2.3/3.1 mm\(^3\) was mounted, where the glass was constrained along its four edges. In the 1980s, similar boundary conditions were reported in the test setups employed by Johar [124,125] and Pal and Pennington [120] to investigate large sized window glass panes at low strain rates, from about 10\(^{-11}\) to 10\(^{-7}\) s\(^{-1}\). An air chamber on one side of the constrained glass pane was pressurised by moving a plungier, until failure of the glass.

In addition, other, less conventional dynamic fatigue load tests have been reported in the literature reviewed here. To these tests belong the investigations conducted by Borchard in 1937 [122], who studied the effect of loading rate on the strength of 1/2-L glass bottles. The author performed his measurements by pressurising the internal volume of the bottle at a constant rate until glass failure, where lower strain rates from about 10\(^{-4}\) to 10\(^{-6}\) s\(^{-1}\) were obtained. One order of magnitude higher strain rates were reported by Thompson and Cousins in 1949 [123] using explosive charges (black powder) placed inside a box, to which a glass pane of size 355.6 × 482.6 × 2.3/3.1 mm\(^3\) was mounted, where the glass was constrained along its four edges to the box. In the 1980s, similar boundary conditions were reported in the test setups employed by Johar [124,125] and Pal and Pennington [120] to investigate large sized window glass panes at low strain rates, from about 10\(^{-11}\) to 10\(^{-7}\) s\(^{-1}\). An air chamber on one side of the constrained glass pane was pressurised by moving a plungier, until failure of the glass.

3.2.1. Definition of loading rate and relative strength

In the literature reviewed here the dynamic fatigue data in each publication are presented differently. That is, the loading rate has been related to the applied mass, the stress rate (slope of the stress-time curve as in Fig. 3b), strain rate, and/or at some cases with respect to the rate of travel of a piston actuator. In the following discussion of the data, no distinction is made between the different methods used to measure the loading rate. Here, the reported data have been converted to strain rate, using a Young’s modulus of \( E = 70 \ \text{GPa} \) (unless otherwise stated) for comparison purposes:

\[
\dot{\varepsilon} = \frac{\dot{\sigma}}{E}
\]

In the case of axisymmetric bending, Poisson’s effects are present, which are accounted for by the following expression, using a Poisson’s ratio of \( \nu = 0.23 \):

\[
\dot{\varepsilon} = \frac{\dot{\sigma}}{E} (1 - \nu)
\]

Moreover, crack properties (as defined by \( \beta \) in Eq. (7)) and specimen size effects, have been made dimensionless using Eq. (8) by normalising dynamic strength with respect to a static strength, \( \sigma_{\text{ort}} \), interpolated at a strain rate of \( \dot{\varepsilon}_0 = 2.86 \times 10^{-5} \ \text{s}^{-1} \) (\( \dot{\sigma}_{\text{ort}} = 2.0 \ \text{MPa} \ \text{s}^{-1} \) for \( E = 70 \ \text{GPa} \), which means that only the rate dependence of the glass strength dominates and other effects are removed.

4. Investigated material characteristics

Over a century numerous tests have been carried out to investigate the behaviour of glass under various test conditions. Whether the tests were looking at crack growth or strength, glass specimens were either subjected to a number of constant loads or constant loading rates, using experimental techniques as discussed in the previous sections. Therefore, the published data of these tests provide information about load duration effects and the effect of test environment.

This section reviews the results from past investigations that looked into the tensile behaviour of soda-lime-silica glass. All the data presented satisfy the inclusion (search) criteria defined in Appendix B, and no limits were set with respect to the acceptable loading rate. These data are available in digital format in the online repository DTU Data [126]. Results from static fatigue tests have confirmed, generally, that increasing the applied load decreases the time to failure. Similar behaviour applies to the dynamic fatigue data, where the strength increases when the loading rate is increased (i.e. decreasing load duration). In both cases, the data follow well a linear line of best fit when using a log-log plot.

In the following sections, the test results are subdivided into the two categories of static and dynamic fatigue. Furthermore, all of the compiled strength data (from the literature review) are compared to the
Fig. 9. Range of experimental loading rates reported in the published dynamic fatigue tests. See also Table A.2.
existing definition of glass strength as typically accepted in the Standards. A few of the reviewed works are highlighted here since they provide further detail to explain the connection between loading rate and Young’s modulus.

4.1. Load duration effects on strength (static fatigue)

4.1.1. Static fatigue data

The static fatigue data (constant stress) is presented in Fig. 10, as a plot of strength (normalised to a ‘60-second’ strength, \( \sigma_{t0} \), as explained in Sec. 3.1.2) as a function of time to failure. A summary of the key parameters related to test condition, applied minimum and maximum stress, and sub-critical crack growth parameters, are given in Appendix A, Table A.3. A common outcome from all the data reviewed, is that the glass strength decreases when the load duration increases, which is a result that is not dependent on test method and/or specimen geometry. This relationship can be described using a power law as defined by Eq. (4), where the time to failure is related to Eq. (1), which defines crack growth through the crack tip stress intensity factor, \( K_I \), Eq. (2).

Failure times span from 2.5 ms (Mould and Southwick [105]) to 270 d (Shand [110]), resulting in a strength increase of about 100% and a reduction of about 50%, respectively, with respect to \( \sigma_{t0} \). However, a greater number of strength data exists for load duration between 1 s and 1 d, which highlights typical results of experiments; for a very short duration, inertia effects must be considered, and for a very long duration space and patience are needed.

For times lower and higher than \( t_0 = 60 \) s, it is clear that the data in Fig. 10 diverges from the general trend seen. However, most of divergent data should not be treated as a scatter. In this plot the test results obtained for different test conditions show deviations, because of the sub-critical crack growth effect, which is highly dependent on environmental conditions, such as temperature and humidity (see Sec. 2). This results in a change of the log-log linear slope.

The results which exhibit the most significant divergence from the trend are those obtained by Gurney and Pearson [127], who investigated the static fatigue behaviour of soda-lime-silica glass in air and vacuum. In the case of the latter n-values where higher, between 40 to around 135 (see Table A.3), confirming that the crack growth rate strongly depends on the environment. This dependence has been validated further, by investigations that have varied humidity in the surrounding air, up to liquid water, which showed that \( n \), between 14.1 and 20.3, decreases with increasing water content [106,108,128–132]. In predicting the design lifetime of a glass element, a constant value of \( n = 16 \) is a reasonable and conservative choice [96].

Other, more extreme, variations in test conditions have been used by Vonnegut and Glastart [133], who studied the effect of temperature on the strength and fatigue of scratched soda-lime-silica glass rods, between \(-190^\circ\) C and \(520^\circ\) C. They found a very strong dependence on temperature, and between \(100^\circ\) C and \(200^\circ\) C, the strength was at a minimum and the fatigue process dominated. When the temperature was outside this range, lower or higher, the effect of delayed failure was less, which was explained by a low reaction activity at the lower temperatures and evaporation of water at the higher temperatures. Complete control of the surrounding atmosphere is extremely difficult. Therefore, in 1958 Charles [129] performed additional experiments at temperatures between \(-170^\circ\) C and \(242^\circ\) C, where a constant atmosphere of saturated water vapour was used in the tests above 0 °C, and below 0 °C the atmosphere was adjusted from saturated water vapour to low humidity air. Similar to Vonnegut and Glastart, the strongest delayed

![Fig. 10. A re-plot of the reviewed static fatigue data of soda-lime-silica glass, as the relative applied stress (see 3.1.2) as a function of time to failure.](image-url)
failure effect together with lowest strength was found at a temperature around 150 °C, while the effect was weaker for higher temperatures, also indicated by an increased n-value in Table A.3.

In addition to environmental conditions, the strength of glass also strongly depends on the surface condition of the glass. The effect of removing surface scratches on glass rods, using an acid solution, has been studied by Ritter and Vrooman [134] and Ritter and Sherburne [107], both concluding that acid-etched glass is less susceptible to static fatigue, where for n an increased value between 31.0 and 37.6 was found. The opposite effect was investigated extensively by Mould and Southwick [105], who tested microscope slides under controlled ambient conditions with six different surface abrasions produced by grit blasting and emery cloth. These tests resulted in the same general fatigue behaviour, however, with differences in slope. Taking a closer look at the data, it is clear that the abrasions produced from the emery cloth are more susceptible to static fatigue than those produced from grit blasting.

Other studies looking into glass strength and surface condition effects have been conducted by Shand [135], Chantikul et al. [111], and Sglavo and Green [113,114], all of these works introduced local surface effects have been conducted by Shand [135], Chantikul et al. [111], and Sglavo and Green [113,114], all of these works introduced local surface effects that have been studied by Ritter and Vrooman [134] and Ritter and Sherburne [107], both concluding that acid-etched glass is less susceptible to static fatigue, where for n an increased value between 31.0 and 37.6 was found. The opposite effect was investigated extensively by Mould and Southwick [105], who tested microscope slides under controlled ambient conditions with six different surface abrasions produced by grit blasting and emery cloth. These tests resulted in the same general fatigue behaviour, however, with differences in slope. Taking a closer look at the data, it is clear that the abrasions produced from the emery cloth are more susceptible to static fatigue than those produced from grit blasting.

In addition to environmental conditions, the strength of glass also strongly depends on the surface condition of the glass. The effect of removing surface scratches on glass rods, using an acid solution, has been studied by Ritter and Vrooman [134] and Ritter and Sherburne [107], both concluding that acid-etched glass is less susceptible to static fatigue, where for n an increased value between 31.0 and 37.6 was found. The opposite effect was investigated extensively by Mould and Southwick [105], who tested microscope slides under controlled ambient conditions with six different surface abrasions produced by grit blasting and emery cloth. These tests resulted in the same general fatigue behaviour, however, with differences in slope. Taking a closer look at the data, it is clear that the abrasions produced from the emery cloth are more susceptible to static fatigue than those produced from grit blasting.

The works summarised in Fig. 10 are in agreement about the general static fatigue behaviour of soda-lime-silica glass. Nevertheless, from the summary the influence of environmental conditions is not apparent. To highlight these environmental effects, Fig. 11 are two plots which divide the relevant data from Fig. 10 into test environments (around room temperature) important for the construction industry: (a) air (40–80% RH) and (b) water (liquid or 100% RH). To estimate the sub-critical crack growth parameter n, the extreme data points have been excluded by only considering values within the interval from the 2.5th to the 97.5th percentile, i.e. the interval of values containing the central 95% of the data. Since these data points are based on different sample sizes, the method of weighted least squares (WLS) is used for the linear regression with \(\sqrt{N}\) as the weight factor, where \(N\) is the sample size provided in the digital datasets [126] (e.g. \(N = 1\) for data points representing single measurements). Thus, for both test environments (water content) the value for \(n\) listed in Table 1 is determined from the resulting slope 1/n according to Eq. (5). As expected, soda-lime-silica glass is less susceptible to static fatigue in humid air than in water, which is also indicated by a lower gradient of the curve in Fig. 11a. This can be explained by the fact that in humid air, less water molecules react with the atomic structure of glass, as compared to a water environment (liquid or 100% RH), resulting in a slower crack growth and thus a longer life time. The values of \(n\) further confirm that the most accepted value of \(n = 16\) is a reasonable and conservative estimate for the design of float glass used in buildings.

According to the model proposed by Overend and Zammit [136] to determine the tensile strength of float glass, it is unlikely that the strength will continue to increase or decrease constantly for a load duration approaching zero or infinity, respectively. For very short duration tests the strength will approach the inert strength of glass and for a very long duration the threshold strength becomes the limiting factor, as also seen from the \(v(K_i)\)-curve in Fig. 2. This leads to a strength interval, which can be expressed as:

\[
\frac{K_{th}}{\sqrt{K_{th0}}} \leq \frac{K_t}{\sqrt{K_{th}}} \leq \frac{K_{th}}{\sqrt{K_{th0}}}
\]

where \(K_{th}\) and \(K_t\) are the threshold crack size and the critical crack size, respectively. The 2.5th and 97.5th percentile values are used to establish the two asymptotes shown in Fig. 11. In the literature review it was found that in most studies the inert strength of glass is unknown.

Table 1

| Test condition | \(n\) | \(a_t^{95}\) | \(a_t^{2.5}\) |
|---------------|------|-------------|-------------|
| Air (40–80% RH) | 21.2 | 38.1 \(\mu\)m | 0.45 mm |
| Water (liquid or 100% RH) | 16.7 | 173.7 \(\mu\)m | 1.41 mm |

Fig. 11. The static fatigue data from Fig. 10, divided into the test environments (a) air (40–80% RH) and (b) water (liquid or 100% RH), are fitted to a cubic function, applying the strength model proposed by Overend and Zammit [136].
Therefore, the data here are normalised with respect to a ‘60-second’ strength, $\sigma_{60}$, see Sec. 3.1.2. For glass tested in air, 40–80% RH, the relative strength is estimated to approach the asymptotes at 0.56 and 1.51. These values are in line with the asymptotes determined by Overend and Zammitt [136] for several initial crack sizes. Similar good agreement to the results from Overend and Zammitt is found for the glass tested in water where the estimated asymptotes are located at 0.66 and 1.74.

Additional information can be drawn from Fig. 11 by applying the strength model proposed by Overend and Zammitt [136]. For example, on the glass there is a distribution of surface flaws, which vary in length. An estimate of the minimum and maximum initial length of the flaws, $a_{\text{min}}^i$ and $a_{\text{max}}^i$, respectively, can be calculated using Eqs. (12) and (13).

$$a_{\text{min}}^i = \frac{I_a}{2(n-2)v_0}$$

$$a_{\text{max}}^i = \frac{I_a}{2(n-2)v_0} \left(\frac{K_{Ib}}{K_{Ic}}\right)^n$$

The calculated minimum and maximum initial surface crack length are given in Table 1, and for both test environments they are determined by assuming a sub-critical crack growth limit $K_{Ib} = 0.25$ MPa m^{1/2} [137] and a fracture toughness $K_{Ic} = 0.75$ MPa m^{1/2} [96]. However, a distinction is made between the crack velocities applied. For the glass tested in air $v_0 = 6$ mm/s, which can be considered a conservative estimate for in-service conditions of float glass in buildings, and for the glass tested in water $v_0 = 30$ mm/s is representative [96].

The minimum to maximum length ranges from micrometres to millimetres. Furthermore, it appears from the values given in Table 1 that for some of the glass specimens tested in water the initial crack length might have been larger compared to those tested in moist air. Nevertheless, the estimated crack length range, for both test environments, is comparable in magnitude and an overlap is present in the millimetre range. According to Petzold et al. [138] these dimensions correspond to micro-cracks from processing, up to visible flaws typically arising from handling and ageing. Relating these crack origins to the glass samples from the studies, i.e. with respect to handling and surface treatment, the magnitude of the estimated initial crack lengths appear reasonable. Hence, the values given in Table 1 provide a suitable basis for the determination of the design lifetime of a glass element using Eq. (4).

### 4.1.2. Crack velocity data

Crack velocity data can also be used to describe the static fatigue behaviour of soda-lime-silica glass (see e.g. Wiederhorn and Bolz [74]). Although, published crack velocity experiments do not provide direct strength measurements, the data from region I in $\nu(K_i)$-curves can be used to estimate the sub-critical crack growth parameters $n$ and $v_0$ (see Sec. 2). A summary of the parameters determined from the literature is provided in Table 2. It is clear that the average value of $n$ is slightly larger for glass tested in moist air as compared to water immersion, which agrees well with the static fatigue data. Furthermore, the listed values for $v_0$ confirm that this parameter is also affected by water content in the environment, as an increase is seen for most of the investigations conducted in water. This behaviour has already been accounted for in the estimate of the initial crack lengths conducted in the previous subsection, using conservative values proposed in the literature, see Sec. 4.1.1.

Based on the relationship given in Eq. (5), which assumes identical cracks for identical conditions, a static fatigue curve from crack velocity experiments can be estimated using $n$ only and neglecting the asymptotes defined by the inert and threshold strengths:

$$\frac{\sigma}{\sigma_{th}} = \left(\frac{I_a}{I_0}\right)^{1/n}$$

with $\sigma_0$ being the strength at a load duration of $t_0 = 60$ s. For each of the studies listed in Table 2 a static fatigue curve was estimated and compared to the static fatigue data from Fig. 11. The comparison is shown in Fig. 12 divided into the test environments (a) air and (b) water.

The estimated static fatigue curves in air are in good agreement with static fatigue data obtained in the same test environment. Variations in slopes are seen, however, they are within the scatter of static fatigue data. Thus, the $n$-values from crack velocity experiments in air provides a good estimate for the static fatigue behaviour of soda-lime-silica for a load duration where a constant decrease in strength can be assumed.

A good agreement between estimated curves and static fatigue data is seen for the experiments conducted in water as well. Although, it seems like the estimates based on data from Wiederhorn [73] (for 100% RH) and Gehrke et al. [83] underestimate the strength for a shorter load duration than 1 s, the variation in slope is still within scatter seen in the static fatigue data. The largest deviation seen, however, is the estimate determined from data published by Singh and Shelly [140], which results in $n = 11.8$. The increase in slope is most likely related to the experimental setup where crack velocities were obtained from cylindrical specimens in a diametral compression test.

---

Table 2

| Reference                  | Test cond. | $n$ | $v_0$ |
|----------------------------|------------|----|-------|
| (a) Test environment: air  |            |    |       |
| Wiederhorn [72]            | Moist air  | 22.3| -     |
| Wiederhorn [73]            | Water      | 22.7| 1.8   |
| Kerkhof et al. [78]        | 50% RH     | 18.1| 2.4   |
| Gehrke et al. [82]         | 50% RH     | 16.7| 0.9   |
| Ullner [84]                | Air        | 19.6| 2.5   |
| Dwivedi and Green [139]    | 64.76% RH  | 20.4| 0.3   |
| **Average:**               |            | 20.0| 1.6   |

| (b) Test environment: water|            |    |       |
| Wiederhorn [72]            | Water      | 17.1| -     |
| Wiederhorn [73]            | Water      | 17.9| 4.3   |
| Wiederhorn [73]            | Water      | 12.0| 3.8   |
| Wiederhorn and Bolz [74]   | Water      | 17.2| 35.3  |
| Wiederhorn and Johnson [75]| Water      | 16.9| 6.8   |
| Freeman [76]               | Water      | 15.6| 6.6   |
| Kerkhof et al. [78]        | Water      | 16.0| 50.2  |
| Simmons and Freeman [79]   | Water      | 17.9| 12.7  |
| Wiederhorn et al. [80]     | Water      | 17.4| 9.7   |
| Gehrke et al. [82]         | Water      | 15.5| 3.1   |
| Gehrke et al. [83]         | Water      | 19.0| 1.8   |
| Singh and Shelly [140]     | Water      | 11.8| 2.5   |
| Ullner [84]                | Water      | 18.4| 14.9  |
| **Average:**               |            | 17.0| 12.6  |

*a* Determined from $\nu(K_i)$-curves using the relationship given by Eq. (1) and assuming a fracture toughness of $K_{Ic} = 0.75$ MPa m^{1/2}. 

---
A large number of dynamic fatigue tests (constant stress rate) have been carried out on soda-lime-silica glass. All the data found in the literature are presented in Fig. 13, where the tensile strength is normalised to a strength, \( \sigma_{\varepsilon_0} \), interpolated or extrapolated at \( \varepsilon_0 = 2.86 \cdot 10^5 \) s\(^{-1} \) (\( \propto 2.0 \text{ MPa s}^{\frac{1}{5}} \) for \( E = 70 \) GPa), as explained in Sec. 3.2.1. Table A.4 in Appendix A is a summary of the key parameters, such as test condition, minimum and maximum failure stress, and the sub-critical crack growth parameters \( n \) and \( v_0 \), from the literature reviewed in this work.

Fig. 13 clearly shows that strength increases with increasing strain rate, i.e. decreasing load duration, which is similar to the behaviour seen in static fatigue tests. Most of the studies have been carried out at strain rates between \( 10^7 \) s\(^{-1} \) and \( 10^3 \) s\(^{-1} \) (quasi-static range of loading according to Fig. 1), where the data are in quite good agreement. The strain rate range of the data in Fig. 13 is quite typical because most research facilities have access to equipment suitable for quasi-static loading, i.e. universal testing machines. When looking at the lowest and highest strain rates in the plot, there are fewer data points because special equipment would be needed. It is also clear that at the extremes of strain rate, the data exhibits a strong divergence from the general trend of the dynamic fatigue curve. Since no distinction has been made here between tests conducted under different conditions, the effect of sub-critical crack growth is again an explanation for the strong divergence in the data. However, at the very high strain rates, the experimental execution also becomes more complex, which is an additional cause of scatter.

Strain rates that have been achieved in experiments range from \( 3.5 \cdot 10^{11} \) s\(^{-1} \) (Johar [125]) to \( 9.9 \cdot 10^2 \) s\(^{-1} \) (Zhang et al. [102]), resulting in a strength reduction of about 40% and an increase of about 175% with respect to the reference strength, \( \sigma_{\varepsilon_0} \), defined in Sec. 3.2.1. Many of the publications found were conducted to study the sub-critical crack growth parameter \( n \) under various conditions and moderate strain rates. In recent years, however, the demand for high strain rate properties of glass has increased, due to an increased threat of blast load scenarios from terror attacks. It has been shown that glass is the cause of many injuries in such terror attacks [141–143]. This recent interest has highlighted that the number of existing published test results are small, for the high strain rate regime, which further increases the demand for such data.

It is interesting to note that the data from Thompson and Cousins [123] diverges strongly from the general trend of the dynamic fatigue behaviour. The significantly steeper curve can be attributed to the experimental setup, where thin window glass panes (see Table A.2) clamped along all four edges were tested in bending, in an explosion test box. Similar thin glass panes (that is, glass thickness is much less than the width and length of the pane) were tested in bending at ambient conditions by Johar [124, 125] and Pal and Pennington [120], resulting in \( n \)-values between 13.4 and 22.6. Comparable values for the crack growth parameter have also been obtained by many other investigators listed in Table A.4, who have tested soda-lime-silica glass in either air or water at moderate temperatures. This also becomes evident from Fig. 13.
where the majority of test results are located in a narrow band.

Apart from varying the water content in the test environment, some also included the effect of temperature. The earliest studies found are from 1935, where Mengelkoch [144] tested glass at two loading rates for temperatures between $190\,^\circ \text{C}$ and $545\,^\circ \text{C}$. The strength reduced to a minimum at $140\,^\circ \text{C}$ and began to increase steadily at higher temperatures. At the same time, Mengelkoch also showed that the strength decreased with loading rate. Later on, in the same year, Eichler [145] conducted experiments with 3–4 different loading rates at $400\,^\circ \text{C}$ and $445\,^\circ \text{C}$, concluding the opposite behaviour at high temperatures, namely
that the strength increases with decreasing loading rate. However, these two studies have not been included in Fig. 13, because the significant difference in testing temperature compared to the other works makes a direct comparison meaningless. Other results on the effect of temperature, between 5 °C and 85 °C, are reported by Ritter et al. [146,147]. Soda-lime-silica specimens with indented and abraded surfaces and two different treatments, annealing and ageing, have been tested. No significant variation in the dynamic fatigue behaviour as a function of temperature was observed since the slope of the data remains nearly unchanged.

Also in dynamic fatigue tests the effect of surface scratches and other mechanical impacts that damages the surface has been subject to a number of studies. It is well-known that the more severe a glass is damaged, the lower its resistance to tensile stresses becomes. But how do these cracks or even the absence of them impact the dynamic fatigue behaviour of soda-lime-silica glass remains an open question. This was investigated by Ritter [148] and Ritter and LaPorte [149] where abraded and acid-etched specimens were tested in air and water, respectively, resulting in slightly larger n-values for the acid-etched glass, see Table A.4. When deriving characteristic fatigue parameters from experiments with constant loading rates, Gehreke et al. [82] included different surface treatments in there studies: emery paper, Vickers indentation, and powder jets. While the general fatigue behaviour with reference to n was almost unchanged, the behaviour was significantly affected by the different initial crack size at low stressing rates. Here, both Vickers indentation and powder jet surface damage showed reduced fatigue behaviour with an increase in the fatigue limit. The application of identical grinding at different angles to the stress direction has been studied by Choi et al. [150], where it has been shown that the dynamic fatigue behaviour is unaffected by the orientation of grinding. Also, well-controlled surface scratches have been applied in a number of dynamic fatigue studies to limit the scatter of the test results and thus improve the precision of the measurements [118,119,151].

A more in-depth studied surface crack is the Vickers indentation, which due to the indentation method produces residual stresses around the crack [113,114,139,152-158]. Based on found publications, it can be concluded in summary that the dynamic fatigue behaviour investigated in air and water is comparable to other surface treatments tested in similar conditions. However, it is important to consider the residual stresses introduced around the crack, in the determination of failure stresses, as it has been shown that the strength level is significantly lower than found for specimens that have been annealed after indentation [114,152]. For more details about the characteristics of post and sub threshold indentation flaws, which constitutes a significant part of the mentioned studies about Vickers indentations, the reader is referred to the cited publications, as it is beyond the scope of this review paper.

Only a few high strain rate publications (above 1 s \(^{-1}\)) on soda-lime-silica glass were found. While publications from Chandan et al. [98], Zongzhe et al. [159], and König [117] show an almost linear dynamic fatigue behaviour that clearly is in line with data found at lower strain rates. The other studies in the high strain rate regime tend to deflect from the general trend. The highest rates of strain were reached by Zhang et al. [102], who investigated cylindrical glass specimens in diametral compression applying a split Hopkinson pressure bar test setup. Based on their findings, shown as individual data points in Fig. 13, two dynamic increase functions (DIF) have been proposed within the ranges (1) \(10^{-5} \text{s}^{-1} \leq \dot{\varepsilon} \leq 3.5 \times 10^{3} \text{s}^{-1}\), and (2) \(3.5 \times 10^{5} \text{s}^{-1} \leq \dot{\varepsilon}\). It is the only study found where a sudden increase in strength is observed. However, this behaviour is found at strain rates that where higher than what other researchers have reported. With similar experiments at only two strain rates, a quasi-static one at around 3.8 \(\times 10^{-5} \text{s}^{-1}\) and a dynamic one at around 5.5 \(\times 10^{5} \text{s}^{-1}\), Peroni et al. [101] also confirmed a strain rate sensitivity for the glass strength, but with an indication of an approaching limit with respect to all other data shown. A similar tendency is seen from the dynamic fatigue curves provided by Meyland et al. [119], where a servo-hydraulic high-speed testing machine was used to test circular specimens with two different surface treatments in axisymmetric bending. An explanation given for the observed increase in strength, is the decrease (or even absence) of sub-critical crack growth effects at high loading rates. Comparing the obtained n-values (see Table A.4) between Peroni et al. and Meyland et al., one will observe substantial higher numbers in relation to the other studies reported. As an increased value for n demonstrates reduced fatigue behaviour, this might further indicate that the data approaches a limit.

As mentioned above, no special attention is given to the test environment for data shown in Fig. 13. While a strain rate sensitivity is clearly seen for the strength of soda-lime-silica glass, the effect of water in the surrounding test medium, which controls the sub-critical crack growth, is less prevailing. Therefore, the same approach as used for the static fatigue data is applied, where in Fig. 14 relevant data from Fig. 13 are divided into the test environments (around room temperature): (a) air (25–67% RH) and (b) water (liquid or 100% RH). Based on data ranging between the 2.5th and 97.5th percentile, the sub-critical crack growth parameter n is once more determined by means of WLS using the weight \(\sqrt{N}\), where N (given in the digital datasets [126]) is the number

**Fig. 14.** The dynamic fatigue data from Fig. 13, divided into the test environments (a) air (25–67% RH) and (b) water (liquid or 100% RH), are fitted to a cubic function. Due to an observed lack of data at high strain rates in (b), the arrow indicates that a limit possibly is not reached.
of tests that is representative for each data point. From the resulting slope $1/(n + 1)$, $n = 18.1$ is found for the glass tested in air. As expected, a slightly lower value of 16.5 is obtained for the glass tested in water, which agrees well with the typical value of $n = 16$ the is recommended for the design of glass elements for buildings.

It is unrealistic to think of the glass strength decreasing continuously for loading rates approaching zero, as also shown by Gehrke et al. [82]. At very low loading rates it is therefore reasonable to assume static load conditions, by which the lower limit can be defined by the threshold strength as in Eq. (11). An upper limit at very high loading rates, as suggested by the Refs. [85,97,98], has not been well validated, although a small indication of it seems to be present in Fig. 13. Above a certain loading rate, however, it must be assumed that sub-critical crack growth effects are negligible because very rapid loading limits the rate at which water can migrate to the crack tip, resulting in an inert environment. Thus, the inert glass strength theoretically becomes the limiting measure for loading rates approaching infinity.

An estimate of these limits, for both test environments, is given by applying the previously mentioned percentiles, as shown in Fig. 14. The lower limits of the strength are found to be identical with a value of 0.65 and are very close to the limits estimated from the static fatigue data in Sec. 4.1.1. The upper limit for the glass tested in air is 2.30, which means that the strength increases by up to 130% as compared to the reference strength, $\sigma_{cr}$. However, the value of 1.65 for the glass tested in water seems in comparison to be quite low. This can be explained by the lack of data seen at the high strain rates, where it is difficult to test glass in a water environment. In Fig. 14b, a dotted line is used to indicate that the upper limit possibly is not reached, along with an arrow on the solid curve indicating that the strength could increase further at higher strain rates. It is obvious that for both test environments more tests are needed in the high strain rate regime; first, in air to rule out the disagreement in dynamic fatigue curves, and then, in water to actually measure well-defined data. Also the low strain rate range needs further attention to obtain a more conclusive threshold strength limit.

Here no estimate of the initial crack length range is determined, as was provided for the static fatigue data. To make such a determination would require additional assumptions concerning the load duration needed for Eqs. (12) and (13), which again would add further undesirable uncertainty to the range estimate.

4.3. Normative definition of the interrelationship between load duration and glass strength

Structural engineers are usually bound by Standards to maintain sufficient safety when designing building structures. A variety of normative definitions do exist that define the interrelationship between the load duration and glass strength. This section of the paper reviews the most current Standards that were available to the authors.

International Standards specifying the load resistance of annealed glass include the European Standards, EN 16612 [160] and the final draft of a new Eurocode 10 for the design of glass structures FrpCEN/TS 19100-1 [161], the American Standard, ASTM E1300-16 [162], and the Australian Standard, AS 1288–2006 [163]. However, there are also a number of national Standards, such as the German Standards, DIN 18008-1 [164] and DIN 18008-4 [165], the Netherlands Standard, NEN 2608 [166], the Austrian Standard, ÖNORM B 3716-1 [167], and the Italian Standard, CNR-DT 210 [168]. Common for all is a load duration factor, often denoted as $k_{mod}$. This factor is used in the defined design equations to scale the fracture resistance of the base material with respect to a predefined duration. Such a factor can be expressed as the strength relative to the inert strength of the glass; however, determining the inert strength experimentally is challenging [136]. Instead it is more convenient to define the load duration factor with respect to a reference strength, $\sigma_{cr}$, for a given load duration that usually is $t_0 = 1 s, 3s$ or 60 s [96].

Fig. 15 is a plot of the factor $k_{mod}$ as function of load duration in hours. The data is static and dynamic fatigue data from Fig. 11 and Fig. 14, and from the calculations defined in the Standards. In addition, the analytical solution based on the empirical power law together with the theory of linear elastic fracture mechanics (LEFM) using $n = 16$ is

![Fig. 15. Load duration factor, $k_{mod}$, as defined by different Standards for annealed glass, compared to static and dynamic fatigue data from Fig. 11 and Fig. 14 as well as an analytical solution based on LEFM.](image-url)
given (see Eq. (5)). Strain rates in the dynamic fatigue data are converted to a load duration by assuming a constant loading rate as depicted in Fig. 2b. Both experimental data and the analytical solution are normalised with respect to a ‘60-second’ strength, which is the less conservative strength normalisation relative to the Standards.

A fairly good agreement is obtained between the experimental data and the empirical power law for \( n = 16 \), again confirming that this choice is reasonable in the design of glass structures in buildings. Furthermore, the comparison in Fig. 15 shows that there are two approaches used to define the load duration dependence:

1. An expression dependent on the load duration, that is defined by a continuous function. This function is an empirical power law and describes sub-critical crack growth in glass, and
2. a more conservative approach where fixed values for given types of load configurations (long-term, medium-term, and short-term) are defined, i.e. a step function.

The Standards based on the continuous function approach, i.e. EN 16612, ASTM E1300-16, AS 1288–2006, NEN 2608, and CNR-DT 210, all use the crack growth exponent \( n = 16 \). No value for \( n \) is to be found in FprCEN/TS 19100-1, but the individual \( k_{mod} \) values nearly overlap with the function defined by EN 16612 and are defined for load duration down to 100 ms (impact loading). For even shorter load duration, e.g. blast loading, it is defined that \( k_{mod} \) can be taken from a transparent and reproducible assessment. However, there are differences in Fig. 15 because of the choice of \( \tau_0 \). The smaller the reference load duration is, the more conservative is the estimate of load resistance. In CNR-DT 210 \( \tau_0 = 0.67 \text{ s} \) forms the basis, whereas both AS 1288–2006 and ASTM E1300-16 uses \( 3 \text{ s} \). Although, the American Standard follows the empirical power law, the maximum value that the load duration factor can take is 1.0. For a shorter duration, e.g. relevant for blast loads, an equivalent 3-second duration design load is to be determined according to ASTM F2248-19 [169]; however, only valid for laminated glass. The longest reference duration of 5 s is found in EN 16612 and NEN 2608. The European Standard is the only one that sets an upper limit of 20 ms, which is an exceptional load duration (relates to, for example, blast loads), resulting in a \( k_{mod} \) factor greater than one. For ordinary load cases, this factor must be between 0.25 and 1.0. Regardless of the choice of \( \tau_0 \), the data from the literature and the Standards are in good agreement down to around 1 ms. In many cases glass must withstand a permanent constant load (e.g. atmospheric pressure in Vacuum Insulated Glass, glass wall load-bearing elements in buildings, etc.). The Standards provide the range in load duration to determine the lifetime to failure of the glass in such cases, often seen up to 50 yr. Nevertheless, it is important to note that in this work, looking through all of the reviewed literature, no experimental data supporting the extrapolations provided in the Standards was found.

When only the type of loading is known, and not the exact duration of applied load, the Australian Standard provides predefined values for short-term (<3 s), medium-term (>3 s and <10 min), and long-term (>10 min) load duration, where the point at which the Standards step change occurs coincides with the curve used when the load duration is exactly known. By doing so, the load duration factors are typically lower than the values obtained from experiments, which means that failure in glass can be determined with greater certainty. In particular, this applies to load duration below 3 s, where the load duration factor is always equal to 1.0. There is even greater certainty in the process described in the German Standard, DIN 18008-1, where \( k_{mod} \) takes the maximum value of 0.70 for short duration, e.g. wind loads. Medium-term and permanent load duration are given the values 0.40 and 0.25, respectively. However, no specific load duration range is specified for these types of load configurations. The ones shown in Fig. 15 are defined according to Schula [170]. More extreme load cases are covered by DIN 18008-4, which is intended for the design of barrier glazing. Here, a \( k_{mod} = 1.8 \) is specified for soft body impact loading on float glass, typically having a load duration between 40 ms and 100 ms [171], as in Fig. 15. This is the only definition in the German Standards for glass that accounts for the strain rate sensitivity previously discussed. In comparison to the values obtained from experiments, the certainty in DIN 18008-4 is less. However, the data in Fig. 15 does not include soft-body impact, which might demonstrate a higher level of certainty for that specific load case. Lastly, the Austrian Standard, ÖNORM B 3716-1, also specifies fixed load duration factors, using a value of 1.0 for short-term duration, 0.6 for both the medium-term and long-term duration, leading to a less flexible estimate of crack growth effects in glass. Using the same load duration as for DIN 18008-1, an overestimate of the \( k_{mod} \) factor is obtained for a load duration above 1 min, and this means that for a very short duration, high level of certainty is again ensured. In conclusion, Fig. 15 shows that all the Standards, except for the Austrian Standard, are in good agreement when considering the long-term behaviour (>1 yr) of float glass.

### 4.3.1. Simplified strength determination using the load duration factor

Some variation in the definition of the load duration factor \( k_{mod} \) is seen between the international and national Standards reviewed. To emphasise the impact of this variation on the design of glass members, a simple example is provided here. In general, the design strength of glass is not only dependent on load duration. However, for simplicity, all other factors that need to be accounted for in the different Standards are disregarded. Taking into account the characteristic bending strength of soda-lime-silica glass \( f_k = 45.0 \text{ MPa} \) (cf. EN 572-1 [172]), a simplified design strength, \( \sigma_f \), is found from the following relationship:

\[
k_{mod} = \frac{\sigma_f}{\sigma_k}
\]  

(15)

Due to larger variations observed in the dynamic load range in Fig. 15, the data given in Table 3 is based on a load duration \( \tau = 100 \text{ ms} \). The American Standard ASTM E1300-16 is excluded from the comparison, as the chosen load duration is out of the defined range. In that case, ASTM F2248-19 is to be used in conjunction with ASTM E1300-16, but this would require detailed knowledge of the blast scenario that is to be designed for and is therefore not done.

Minor variations are seen in the simplified design strengths found by the Standards using a continuous function of \( k_{mod} \) that is related to the empirical power law described in Sec. 2. With the same approach, the analytical solution based on LEFM with \( n = 16 \), representing the individual data points from the reviewed static and dynamic fatigue tests, results in a larger \( \sigma_f \). However, this deviation is related to the choice of \( \tau_0 = 60 \text{ s} \). The lowest values for the simplified design strength are found by the Standards that define a step function for the load duration factor. This is a rather conservative approach, which does not properly take into account the measured time-dependencies as they are shown in Fig. 11 and Fig. 14. The German Standard DIN 18008-4, accounting for soft

| Standard | \( k_{mod}(100 \text{ ms}) \) | \( \sigma_f \) (MPa) |
|----------|-----------------|------------------|
| EN 16612/2019 | 1.28 | 57.6 |
| FprCEN/TS 19100-1:2021 | 1.20 | 54.0 |
| AS 1288–2006 (load duration) | 1.24 | 55.8 |
| CNR-DT 210/2013 | 1.12 | 50.8 |
| LEFM with \( n = 16, \text{ Eq. (5)} \) | 1.49 | 67.1 |
| AS 1288–2006 (load configuration) | 1.00 | 45.0 |
| ÖNORM B 3716-1:2016 | 1.00 | 45.0 |
| DIN 18008-1:2010 | 0.70 | 31.5 |
| DIN 18008-4:2013 | 1.80 | 81.0 |
body impacts, determines the highest value of $\sigma_f$, however, $k_{\text{mod}}$ is only valid over a very short load duration.

### 4.4. Loading rate effects on the Young’s modulus

There are few publications that report the Young’s modulus of soda-lime-silica glass at various loading rates. The authors have reviewed three publications: Makovička and Lexa [34], performed glass tests in three-point bending, König [117], used a universal high-speed testing machine on ‘dog-bone’ shaped specimens, and Zhang et al. [102], performed diametral compression tests on cylindrical specimens in a split Hopkinson pressure bar setup. The data from these works are summarised in Fig. 16.

Data from Makovička and Lexa, and König, are presented as averaged values, and the error bars are the standard deviation. However, the results from Zhang et al. are not averaged because the strain rate much more varied. A slight increase in Young’s modulus is observed from the data in König during the three highest obtained strain rates. The data from Makovička and Lexa, on the other hand, exhibit a decrease in stiffness with increasing strain rate. No clear tendency is visible in the scatter in the data from Zhang et al., as the individual data points are clustered around 60 GPa at strain rates between $10^1$ s$^{-1}$ and $10^3$ s$^{-1}$. This disagreement in these three results could be attributed to the different experimental techniques employed. Generally, the Young’s modulus of glass is not found to be sensitive to the rate of loading, as also stated by Mainstone [173]. The European Standard EN 572-1 [172] defines a rate insensitive modulus of elasticity of 70 GPa for soda-lime-silica glass, which is used in comparison purposes also shown in Fig. 16.

### 5. Conclusion

In this work an extensive literature review, based on 92 publications dating back to 1899, has been presented. The data from these publications were reviewed in detail to compile a summary of current state-of-the-art understanding of the time-dependent tensile behaviour of soda-lime-silica glass, a material used routinely in civilian infrastructure. In general, it is concluded that glass can be characterised using two test methods: (1) the static fatigue test, constant applied stress, and (2) the dynamic fatigue test, constant stress rate. From these tests the interrelationship between the load duration and the strength of the glass specimen can be readily defined for in-service glass components. It was found that most researchers prefer using the three- and four-point bending, and axisymmetric bending configurations, when testing glass. In static fatigue tests data with load duration between 2.5 s and 270 d were produced. The dynamic fatigue tests were performed using a universal testing machine and more advanced test machines, such as a split Hopkinson pressure bar, at strain rates between $3.5 \times 10^{-11}$ s$^{-1}$ and $9.9 \times 10^3$ s$^{-1}$.

The static fatigue tests on soda-lime-silica glass are, in general, sensitive to the load duration. On a double-logarithmic scale, a linear decrease in strength was confirmed for increasing load duration. With respect to a ‘60-second’ strength, an increase of about 100% and a reduction of about 50% has been achieved. Furthermore, the sub-critical crack growth parameter $n$ indicates that glass tested in air (40–80% RH, $n = 21.2$) is less susceptible to static fatigue as compared to tests in water (liquid or 100% RH, $n = 16.7$). Crack velocity experiments, also considered as static fatigue tests, have further confirmed that the crack growth parameter $n_0$ is affected by the amount of water in the surrounding environment.

Similarly, the dynamic fatigue tests are, in general, sensitive to the loading rate, where glass strength increases with loading rate (linearly on a log-log scale), i.e. decreasing load duration. At the lowest and highest rates, a strength reduction of about 40% and an increase of about 175% have been obtained, respectively; this is calculated with respect to a strength corresponding to a strain rate of $2.86 \times 10^{-5}$ s$^{-1}$ ($\alpha=2.0$ MPa s$^{-1}$ for $E = 70$ GPa). These dynamic fatigue tests confirmed that $n$ decreases with an increasing water content; from the literature $n = 18.1$ for air (25–67% RH) and $n = 16.5$ for water (liquid or 100% RH).

In the reviewed works many results were obtained at moderate load duration and loading rates. Only a few studies also attempted to measure beyond the current strength limits. Estimates for possibly reached strength limits (asymptotes) were determined using the central 95% data range. Static fatigue data obtained in air and water yielded lower and upper relative strength limits at 0.56 and 1.51, and 0.66 and 1.74, respectively. Dynamic fatigue data obtained in air resulted in limits at 0.65 and 2.30, while it was only possible to estimate a lower limit at 0.65 for the data obtained in water. However, much more testing is needed to address properly the limits; especially at the high loading rates relevant to blast and impact events. Furthermore, it was shown that glass strength data, both from static and dynamic fatigue tests, agree with most of the load duration factors specified in several international and national Standards. These Standards are routinely used by civil engineers to design glass structures that use soda-lime-silica glass. Lastly, the three studies which report Young’s modulus data for soda-lime-silica glass, did not find a significant loading rate effect.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgements

The first author gratefully acknowledges the financial support provided by the Innovation Fund Denmark (IFD) [grant No. 8053-00088B], Ramboll Fonden [grant No. 2018-51], and the Danish engineering consultancy Ramboll Denmark A/S, Private & Public Buildings East.
Appendix A. Experimental details and results

Tables A.1 and A.2 in the following provide the detail of the static and dynamic fatigue tests reviewed: specimen geometry, surface treatment, load configuration, and load application. Moreover, Tables A.3 and A.4 summarises the key numbers from the various tests: test condition, minimum and maximum failure stress, and parameters defining the sub-critical crack growth ($n$ and $y_0$).

Table A.1
A detailed summary of the reviewed static fatigue tests reported on soda-lime-silica glass.

| Year  | Reference         | Specimen                  | Treatment          | Load configuration | Load application                  |
|-------|-------------------|---------------------------|--------------------|--------------------|-----------------------------------|
| 1899  | Grenet [70]        | Ø4.5 mm (in average), glass rods | Untreated          | 3-point bending    | Dead-weight (water)               |
| 1935  | Black [104]        | 254.0 × 50.8 × 2.8 mm³, glass plates | Untreated          | 3-point bending    | Dead-weight cantilevered bending device (water) |
| 1935  | Preston [71]       | 406.4 × 50.8 × 6.4 mm³, glass plates | Polished           | 3-point bending    | Dead-weight                       |
| 1940  | Holland and Turner [176] | 100 × 8 × 0.265–0.285 mm³, glass samples | Ground and polished edges | 3-point bending    | Dead-weight (lead shot)          |
| 1946  | Baker and Preston [139] | Ø5.6 mm × 152.4 mm, annealed glass rods | As-received        | 3-point bending    | Dead-weight (sand); dynamic loudspeaker |
| 1946  | Voneugut and Glathart [133] | Ø5.6 mm × 152.4 mm, glass rods | Abraded            | 3-point bending    | Dynamic loudspeaker               |
| 1949  | Gurney and Pearson [127] | Ø6.4 mm × 76.2 mm, glass rods | Untreated          | 4-point bending    | –                                 |
| 1954  | Shand [110]        | Ø6.4 mm, annealed glass rods | –                  | Bending            | –                                 |
| 1958  | Charles [129]      | Ø2.5 mm × 101.6 mm, glass rods | Abraded            | 4-point bending    | Dead-weight                       |
| 1959  | Mould and Southwick [105] | 76.2 × 25.4 × 1 mm², annealed microscope slides | Various abrasions | 3-point bending    | Dead-weight cantilevered bending device; electromagnetic loader |
| 1961  | Mould [106]        | 76.2 × 25.4 × 1 mm², annealed microscope slides | Abraded            | 3-point bending    | Dead-weight cantilevered bending device; electromagnetic loader |
| 1961  | Shand [135]        | 114.3 × 19.1 × 2.4 mm³, glass strips | Cleaved cracks; as-received and re-anaealed | 4-point bending    | Screw traverse testing machine |
| 1969  | Ritter and Vrooan [134] | Ø3 mm × 165.1 mm, glass rods | Acid-etched        | 4-point bending    | Dead-weight cantilevered bending device |
| 1971  | Ritter and Sherburne [107] | Ø3 mm × 152.4 mm, annealed glass rods | Acid-etched        | 4-point bending    | Dead-weight cantilevered bending device |
| 1976  | Pavelchev and Doremus [108] | Ø3 mm × 50 mm, glass rods | Abraded            | 4-point bending    | Dead-weight cantilevered bending device |
| 1978  | Jakus et al. [130] | –                          | –                  | –                  | –                                 |
| 1980  | Richter [131]      | –                          | One side notched (a = 1.2–3.5 mm) | Uniaxial tensile test | Dead-weight |
| 1981  | Chantikul et al. [111] | Ø50 mm × 3 mm, glass discs | Vickers indentation (5 N) | Axysymmetric bending | Universal testing machine |
| 1989  | Ikeda and Igaki [112] | Ø21 mm × 2.8 mm, glass discs | Indented-induced flaw | Diametral compression and axysymmetric bending | Universal testing machine |
| 1995  | Sglavo and Green [113] | 63.5 × 6.4 × 2.4 mm³, annealed glass bars | Vickers indentation (9.8 N) | 4-point bending | Universal testing machine |
| 1997  | Chen and Matsumura [109] | 60 × 10 × 5 mm², glass bars | Scratched           | 3-point bending    | Dead-weight cantilevered bending device |
| 1999  | Sglavo and Green [114] | 50 × 5 × 2 mm³, annealed glass bars | Vickers indentation (9.8 N) | 4-point bending | Universal testing machine |
| 2000  | Fink [132]         | 1000 × 360 × 4 mm², glass plates | Corundum treatment | 4-point bending    | Dead-weight                       |

* Original work published by Phillips in 1937 [175].

Table A.2
A detailed summary of the reviewed dynamic fatigue tests reported on soda-lime-silica glass.

| Year  | Reference            | Specimen                  | Treatment          | Load configuration | Load application                  |
|-------|----------------------|---------------------------|--------------------|--------------------|-----------------------------------|
| 1899  | Grenet [70]          | 24.5 × 2.5 mm² and Ø4.8 mm (cross-sectional areas in average), glass plates and rods | –                  | 3-point bending    | Bucket filled with water         |
| 1934  | Apelt [177]          | Glass rods, $A_s = 1.31–1.48$ mm² | Natural fire polishing | Uniaxial tensile test | Tearing apparatus        |
| 1935  | Black [104]          | 254.0 × 50.8 × 2.8 mm³, glass plates | Untreated          | 3-point bending    | Lever arm loaded with water      |
| 1937  | Borchard [122]       | 1/2.4 glass bottles (225 g), 3.5 mm thick | Pressure test     | Pressure testing unit with water |                             |
| 1949  | Thompson and Cousins [123] | 2.3/3.1 × 355.6 × 482.6 mm², glass panes | –                  | Plate bending test | Explosion test box               |
| 1958  | Charles [94]         | Ø2.54 mm × 101.6 mm, glass rods | Abraded            | 4-point bending    | Bending device                   |
| 1969  | Ritter [148]         | Ø3 mm × 101.6 mm, annealed glass rods | Abraded and acid-etched | 4-point bending    | Universal testing machine       |
| 1974  | Ritter [178]         | Ø3 mm × 127 mm, annealed glass rods | Abraded, different surface coatings | 4-point bending    | Universal testing machine       |
| 1975  | Evans and Johnson [77] | –                          | Abraded            | 4-point bending    | –                                 |
| 1975  | Ritter and LaPorte [149] | Ø6 mm × 101.6 mm, annealed glass rods | Abraded            | 4-point bending    | Universal testing machine       |

(continued on next page)
| Year | Reference | Specimen | Treatment | Load configuration | Load application |
|------|-----------|----------|-----------|--------------------|------------------|
| 1975 | Tummala and Foster [179] | $50.8 \times 3.18 \times 3.18 \text{ mm}^3$, glass bars | As-received and annealed | 3-point bending | Universal testing machine |
| 1975 | Yamada [180] | $6.4 \times 88.9 \text{ mm}$, glass rods | As-received | 4-point bending | Screw-driven mechanical tester |
| 1978 | Chandan et al. [185] | $10 \times 10 \times 55 \text{ mm}^3$ (standard Charpy size), float glass bars | Ground | 3-point bending | Universal testing machine and pendulum impact machine |
| 1978 | Jakus et al. [130] | – | – | – | – |
| 1979 | Hagan et al. [137] | $5 \times 10 \times 130 \text{ mm}^3$, annealed glass bars | Vickers indentation (2–20 N) | 4-point bending | – |
| 1979 | Woekel and Eisenheimer [182] | $1100 \times 360 \text{ mm}^3$, glass plates with various thicknesses | As-delivered and different abrasions | 4-point bending | – |
| 1980 | Marshall and Lown [152] | $50 \times 5 \times 5 \text{ mm}$, float glass discs | Vickers indentation (5 N); as-indented and annealed | Axissymmetric bending | Universal testing machine |
| 1981 | Johar [124] | $2440 \times 1525 \times 6 \text{ mm}^3$, float glass panels | Untreated | Plate bending test | Hydraulically driven piston |
| 1981 | Kerkhof et al. [178] | $100 \times 100 \times 5 \text{ mm}^3$, squared float glass plates | $60 \text{ mm long and 0.1 mm deep scratch}$ | Axissymmetric bending | Universal testing machine |
| 1981 | Marshall and Lown [183] | $50 \times 5 \times 5 \text{ mm}$, float glass discs | Abraded | Axissymmetric bending | Universal testing machine |
| 1982 | Dabbas et al. [153] | $55 \times 215 \text{ mm}$, annealed glass rods | Acid-etched and Vickers indentation (0.05–10 N) | 4-point bending | Universal testing machine |
| 1982 | Dabbas and Lown [154] | $55 \times 215 \times 6 \text{ mm}$, annealed glass rods | Acid-etched and Vickers indentation (0.15 and 0.25 N) | 4-point bending | Universal testing machine |
| 1982 | Johar [125] | $2440 \times 1525 \times 6 \text{ mm}^3$, float glass panels | Untreated | Plate bending test | Hydraulically driven piston |
| 1983 | Symonds et al. [184] | $50 \times 10 \times 3 \text{ mm}$, annealed glass bars | Indentation line flaws (P = 5 N) | 4-point bending | – |
| 1985a | Ritter et al. [185]. | $75 \times 25 \times 1.0 \text{ mm}^3$, annealed microscope slides | Ground edges | 4-point bending | Universal testing machine |
| 1985b | Ritter et al. [146]. | $57 \times 57 \times 3 \text{ mm}^3$, squared glass plates | Vickers indentation (10 N); aged and annealed | Axissymmetric bending | Universal testing machine |
| 1986a | Ritter et al. [155] | $75 \times 50 \times 1 \text{ mm}^3$, annealed microscope slides | Acid-etched and Vickers indentation (0.2 N) | Axissymmetric bending | Universal testing machine |
| 1986b | Ritter et al. [147] | $75 \times 50 \times 1 \text{ mm}^3$, microscope slides | Abraded in air; aged and annealed | Ball-on-ring bending test | Universal testing machine |
| 1986b | Zongehe et al. [159] | $100 \times 20 \times 5 \text{ mm}$, glass samples | Vickers indentation | 3-point bending | – |
| 1987 | Gehrke et al. [82] | $55 \times 5 \times 5 \text{ mm}$, round glass bars | Abraded with emery paper | 3-point bending | – |
| 1987 | Ikeda et al. [185] | $40 \times 20 \times 2.7 \text{ mm}^3$ and $38 \times 8 \times 2.8$ mm, glass plates and discs | Vickers indentation | 4-point bending and axissymmetric bending | Universal testing machine |
| 1987 | Ritter et al. [156] | $75 \times 50 \times 1 \text{ mm}^3$, annealed microscope slides | Acid-etched and Vickers indentation (0.15, 0.25, and 0.35 N) | Axissymmetric bending | Universal testing machine |
| 1988 | Pal and Pennington [120] | $812.8 \times 685.8 \times 2.2 \text{ mm}^3$, glass plates | – | Plate bending test | Universal testing machine and drop test facility |
| 1989 | Ikeda et al. [187] | $40 \times 20 \times 2.7 \text{ mm}^3$ and $38 \times 8 \times 2.8$ mm, glass plates and discs | Vickers indentation | 4-point bending and axissymmetric bending | Universal testing machine |
| 1992 | Choi and Salem [137] | $75 \times 25 \times 1 \text{ mm}^3$, annealed microscope slides | Vickers indentation (19.6 N) | 4-point bending | Universal testing machine |
| 1992 | Ikeda et al. [188] | $21 \times 28 \times 3 \text{ mm}$, glass slides | Vickers indentation | 4-point bending and axissymmetric bending | Universal testing machine |
| 1992 | Makovicka and Lexa [34] | Glass beam samples | – | Bending | – |
| 1994 | Nemeth et al. [189] | $50 \times 50 \times 1.5 \text{ mm}^3$, squared glass plates | – | Axissymmetric bending | – |
| 1995 | Dvirvedi and Green [139] | $60 \times 7 \times 2.2 \text{ mm}^3$, annealed glass bars | Natural flaws and Vickers indentation (9.8 N) | 4-point bending | Universal testing machine |
| 1995 | Li et al. [190] | $53 \times 60 \times 2.2 \text{ mm}^3$, heat treated glass rods | Abraded | 4-point bending | Universal testing machine |
| 1995 | Sglavo and Green [113] | $63.5 \times 6.4 \times 2.4 \text{ mm}^3$, annealed glass bars | Vickers indentation (9.8 N) | 4-point bending | Universal testing machine |
| 1997 | Choi et al. [191] | $25 \times 1 \times 1 \text{ mm}^3$, glass discs | – | Axissymmetric bending | – |
| 1997 | Liu [192] | $90 \times 20 \times 2 \text{ mm}^3$, glass specimens | Unnotched | 3-point bending | Universal testing machine |
| 1997 | Sglavo et al. [158] | $50 \times 5 \times 2 \text{ mm}^3$, glass bars | Vickers indentation (9.8 N); as-indented | 4-point bending | Universal testing machine |
| 1999 | Sglavo and Green [114] | $50 \times 5 \times 2 \text{ mm}^3$, glass bars | Vickers indentation (9.8 N); as-indented and annealed | 4-point bending | Universal testing machine |
| 2000 | Choi et al. [150] | $48 \times 8 \times 5 \text{ mm}^3$, float glass specimens | Surface ground at different angles (0, 30, 60 and 90°) | 4-point bending | Universal testing machine |
| 2001 | Schneider [171] | $300 \times 300 \times 10 \text{ mm}^3$, drilled float glass plates | Unreated | Axissymmetric bending | – |
| 2002 | Akcalay and Gulati [193] | $100 \times 20 \times 3 \text{ mm}^3$, float glass specimens | Ground and V-belt edge finish | 4-point vertical bending | Universal testing machine |
| 2002 | Krohn et al. [151] | $76.3 \times 76.3 \times 3.89 \text{ mm}^3$, squared glass plates | Vickers indentation (300 N) | Axissymmetric bending | Universal testing machine |
| 2006 | Haldemann [127] | $200 \times 200 \times 6 \text{ mm}^3$, squared glass plates | As-received | Axissymmetric bending | Universal testing machine |
| 2011 | Peroni et al. [101] | $9 \times 5 \times 10 \text{ mm}$, glass cylinders | Surface ground | Diametral compression | Universal testing machine and SHPB test setup |
| 2012 | Konig [117] | $8 \times 8 \times 8 \text{ mm}$, dog-bone glass specimens | Untreated | Uniaxial tensile test | Universal high-speed testing machine |
| 2012 | Zhang et al. [102] | $15 \times 15 \times 15 \text{ mm}$, glass cylinders | Surface ground | Diametral compression | Universal testing machine and SHPB test setup |
| 2015 | Hulcken [194] | $250 \times 250 \times 6 \text{ mm}^3$, squared glass plates | Pre-damaged | Axissymmetric bending | Universal testing machine |

(continued on next page)
### Table A.2 (continued)

| Year     | Reference            | Specimen                          | Treatment                          | Load configuration         | Load application                        |
|----------|----------------------|------------------------------------|------------------------------------|----------------------------|------------------------------------------|
| 2019     | Forch [118]          | 1000 × 360 × 4 mm³, float glass plates | Corundum treatment                 | 4-point bending            | High-speed testing machine (up to 1 m/s) |
| 2019     | Meyland et al. [119] | φ45 mm × 3 mm, float glass discs    | As-received and pre-damaged         | Axisymmetric bending       | High-speed testing machine (up to 5 m/s) |
| 2020     | Brokmann et al. [195] | φ80 mm × 1.8 mm, annealed glass discs | Vickers indentation (9.8 N)         | Axisymmetric bending       | Universal testing machine                |

### Table A.3

Summary of key numbers of the reviewed soda-lime-silica glass static fatigue tests.

| Year     | Reference        | Test condition                          | Applied stress [MPa] | SCG² parameters |
|----------|------------------|-----------------------------------------|----------------------|-----------------|
| 1899     | Grenet [70]      | –                                       | 19.5                 | 43.0            | 10.8 \(\alpha\) |
| 1935     | Black [104]      | –                                       | 24.2                 | 34.6            | –               |
| 1935     | Preston [71]     | –                                       | 37.4                 | 82.0            | 10.0 \(\alpha\) |
| 1940     | Holland and Turner [176] | –                                 | 26.2                 | 87.3            | 11.3 \(\alpha\) |
| 1946     | Baker and Preston [129] | 23.9 °C, water                      | 44.5                 | 137.2           | 14.1 \(\alpha\) |
| 1946     | Vonnegut and Glastart [133] | –, 190 °C                            | 91.3                 | 99.8            | 76.5 \(\alpha\) |
| 1949     | Gurney and Pearson [127] | Atmospheric pressure, no prior vacuum treatment | 41.7                 | 96.5            | 18.1 \(\alpha\) |
| 1954     | Shand [110]      | –                                       | 34.9                 | 103.6           | 15.9 \(\alpha\) |
| 1958     | Charles [129]    | 22 °C, 50% RH                          | 55.9                 | 77.9            | 17.4 \(\alpha\) |
| 1959     | Mould and Southwick [105] | –, 23 °C, distilled water (abr. (a): severe) | 39.2                 | 69.3            | 17.5 \(\alpha\) |
| 1961     | Mould [106]      | 0.5% RH                                 | 35.2                 | 66.3            | 20.3 \(\alpha\) |
| 1969     | Ritter and Vrooman [134] | Liquid water                          | 31.2                 | 66.9            | 17.2 \(\alpha\) |
| 1971     | Ritter and Sherborne [107] | Room temp., controlled humidity (as-received) | 43.0                 | 91.0            | 23.5 \(\alpha\) |
| 1976     | Pavelechek and Doremus [108] | Room temp., controlled humidity (re-annealed) | 28.1                 | 57.6            | 14.2 \(\alpha\) |
| 1978     | Jakus et al. [130] | Room temperature, water                | 38.7                 | 59.6            | 18.1 \(\alpha\) |
| 1980     | Richter [131]    | 40-60% RH                               | 38.7                 | 59.6            | 18.1 \(\alpha\) |
| 1981     | Chantiikul et al. [111] | Water                                 | 36.7                 | 64.1            | 18.4 \(\alpha\) |
| 1989     | Ikeda and Igaki [112] | Distilled water (as-indented)         | 23.8                 | 44.9            | 13.9 \(\alpha\) |
| 1995     | Sglavo and Green [113] | Water (indented in air)                | 20.9                 | 37.6            | –               |
| 1997     | Chen and Matsumura [109] | Water (indented in water, annealed)    | 28.5                 | 44.6            | 18.2, 9.5      |
| 1999     | Sglavo and Green [114] | Deionized water (annealed)             | 31.8                 | 43.3            | 18.7 \(\alpha\) |

(continued on next page)
Table A.3 (continued)

| Year  | Reference | Test condition | Failure stress [MPa] | SCG parameters |
|-------|-----------|----------------|---------------------|----------------|
|       |           |                | $\sigma_{f}^{\infty}$ | $\sigma_{f}^{\max}$ | $\eta$ [-] | $v_0$ [mm/s] |
| 2000  | Fink [132]| Deionized water (as-indentated) | 21.6 | 34.6 | 14.0$^c$ | – |
| 1975  | Evans and Johnson [97] | 1% RH | 15.0 | 30.0 | 16.4 | – |
| 1975  | Ritter [148] | Room temp., air (abraded) | 13.5 | 30.0 | 15.6 | – |

$^a$ SCG = sub-critical crack growth.
$^b$ Estimated by means of least squares fit using Eq (5).
$^c$ Original work published by Phillips in 1937 [175].
$^d$ Based on published $K_I$-data, a relative strength ($K_I$ divided by $K_{0c}$) is estimated using $K_{0c} = 0.75$ MPa m$^{1/2}$.

Table A.4

Summary of key numbers of the reviewed soda-lime-silica glass dynamic fatigue tests.

| Year  | Reference | Test condition | Failure stress [MPa] | SCG parameters |
|-------|-----------|----------------|---------------------|----------------|
|       |           |                | $\sigma_{f}^{\infty}$ | $\sigma_{f}^{\max}$ | $\eta$ [-] | $v_0$ [mm/s] |
| 1899  | Grenet [70] | Glass plates at unk. conditions | 28.9 | 78.4 | 11.2$^e$ | – |
| 1934  | Apelt [177] | Glass rods at unk. conditions | 33.0 | 83.4 | 6.9$^e$ | – |
| 1935  | Black [104] | Room temperature | 44.8 | 74.2 | 10.1$^e$ | – |
| 1937  | Borchard [122] | 10 °C | 2.4 | 3.0 | 30.6$^e$ | – |
| 1949  | Thompson and Cousins [123] | Single strength glass at unk. cond. | 6.2 | 3.1 | 10$^{-2}$ | – |
| 1958  | Charles [94] | 25 °C, water vapour | 75.2 | 97.3 | 16.0 | – |
| 1969  | Ritter [148] | Room temp., air (abraded) | 86.6 | 114.0 | 11.9 | – |
| 1974  | Ritter [178] | Room temp., wet (coating: silicone) | 70.5 | 107.4 | 14.4 | – |
| 1975  | Evans and Johnson [97] | 1% RH | 51.1 | 96.9 | 16.5$^e$ | – |
| 1975  | Ritter and LaPorte [149] | Distilled H$_2$O (abraded) | 60.3 | 97.1 | 13.0 | – |
| 1979  | Hagan et al. [181] | Water | 56.1 | 87.1 | 15.9 | – |
| 1980  | Marshall and Lawn [152] | Deionized water | 75.7 | 110.0 | 13.5 | – |
| 1981  | Johar [124] | Water (as-indentated glass) | 44.2 | 78.6 | 17.9 | 2.4 |
| 1981  | Kerkhof et al. [78] | Water | 28.6 | 62.0 | 13.7 | 55.0 |
| 1981  | Marshall and Lawn [152] | Water | 5.4 | 10$^{-3}$ | 6.6 | 22.6$^e$ | – |
| 1982  | Dabbs et al. [153] | Distilled water | 34.5 | 251.9 | 14.0 | 31.6 |
| 1982  | Dabbs and Lawn [154] | Distilled water | 233.7 | 638.1 | 9.0 | – |
| 1985a | Ritter et al. [185] | Room temp., dist. water (surface) | 87.0 | 104.0 | 17.7 | 10.7 |
| 1985b | Ritter et al. [146] | Room temp., dist. water (overall) | 64.9 | 93.1 | 15.5 | 0.5 |
| 1985b | Ritter et al. [146] | Room temp., dist. water (indented, annealed) | 62.0 | 88.1 | 16.8 | 1.8 |
| 1986a | Ritter et al. [155] | 5 °C, dist. water (subthreshold flaws) | 62.6 | 111.0 | 10.5 | 13.7$^f$ |
| 1986b | Ritter et al. [147] | 5 °C, dist. water (abraded, annealed) | 86.3 | 109.9 | 24.7$^f$ | – |

(continued on next page)
| Year  | Reference       | Test condition                  | Failure stress [MPa] | SCG parameters |
|-------|-----------------|---------------------------------|----------------------|---------------|
|       |                 |                                 | &sigma;f            | &sigma;f/2    | n [-] | v0 [mm/s] |
| 1987  | Ikeda et al. [186] | Air (axisymmetric bending)      | 46.7                 | 63.4          |       |         |
|       |                 |                                | 43.1                 | 54.7          |       |         |
|       |                 | Water (4-point bending)        | 39.9                 | 50.0          |       |         |
| 1987  | Ritter et al. [156] | 25 °C, dist. water (low strength, subthreshold, & P = 0.25 N) | 69.7                 | 111.1         | 13.4  |       |
|       |                 |                                 | 59.6                 | 103.3         | 11.5  |       |
|       |                 |                                 | 69.9                 | 124.0         | 11.4  |       |
|       |                 |                                 | 64.0                 | 112.1         | 11.5  |       |
| 1992  | Choi and Salem [157] | Room temperature, alcohol     | 42.0                 | 52.5          | 20.2 (26.3)^2 | 2.2   |
|       |                 | Room temperature, air         | 39.8                 | 51.8          | 16.2 (20.9)^2 | 16.2  |
|       |                 | Room temperature, acetone     | 38.1                 | 47.8          | 19.3 (25.1)^2 | 24.0  |
| 1992  | Ikeda et al. [188] | Air (diametral compression)    | 26.7                 | 34.2          |       |         |
|       |                 | Water (diametral compression)  | 24.1                 | 34.3          | 31.2  |       |
| 1992  | Makovska and Lexa [34] | –                               | 35.1                 | 64.6          | 13.4^3 |       |
| 1994  | Nemeth et al. [189] | Room temp., distilled water    | 163.6                | 289.9         | 11.3^3 |       |
| 1995  | Dwivedi and Green [139] | Room temp., air (natural flaws) | 96.1                 | 160.9         | 21.8  | 2.6    |
| 1995  | Li et al. [190]  | Room temp., 25–30% RH (T = 470 °C) | 52.3                 | 67.9          | 11.0  |       |
| 1995  | Sglova and Green [113] | Deionized water (indented in air) | 32.4                 | 50.8          | 14.3 (18.8)^3 | 14.3  |
| 1997  | Choi et al. [191] | Room temp., distilled water    | 46.5                 | 251.9         | 16.4  |       |
| 1997  | Lü [192]        | –                               | 56.0                 | 68.2          | 25.0  |       |
| 1999  | Sglova et al. [156] | Deionized water                | 34.5                 | 56.3          | 13.7 (18.0)^6 | 19.0  |
| 1999  | Sglova and Green [114] | Deionized water (annealed)     | 37.8                 | 62.6          | 15.2 (19.9)^6 | 6.4   |
| 2000  | Choi et al. [150] | Deionized water (as-implanted) | 27.8                 | 53.9          | 15.3 (20.1)^6 | 28.8  |
| 2001  | Schneider [171] | Ambient temp., water (grid angle 0°) | 61.8                 | 100.9         | 13.4  |       |
|       |                 | Ambient temp., water (grid angle 30°) | 59.2                 | 95.5          | 13.3  |       |
|       |                 | Ambient temp., water (grid angle 60°) | 41.2                 | 66.3          | 13.2  |       |
| 2002  | Akccakaya and Gulati [193] | Room temp., 100% RH (V-belt)   | 29.5                 | 44.0          | 16.2  |       |
|       |                 | Room temp., 100% RH (ground)   | 30.6                 | 53.5          | 13.5  |       |
| 2002  | Krohn et al. [151] | Room temp., (air side)         | 49.8                 | 91.5          | 21.7  |       |
|       |                 | Room temp., (air side)         | 50.4                 | 88.9          | 21.6  |       |
| 2006  | Haldimann [137] | 23.4–23.8 °C, 51.4–54.7% RH (ambient) | 55.3                 | 103.2         | 2.5^5 |       |
|       |                 | 23.2–23.9 °C, 51.7–54.7% RH (dry/coated) | 85.1                 | 153.4         | 7.6   |       |
| 2011  | Peroni et al. [101] | Air at ambient conditions       | 47.3                 | 98.1          | 27.4^4 |       |
| 2012  | König [117]      | Air at ambient conditions       | 105.4                | 199.6         | 19.7^0 |       |
| 2012  | Zhang et al. [102] | Air at ambient conditions       | 18.2                 | 41.5          |       |       |
| 2015  | Hülken [194]    | 22.7 °C, 50% RH                | 30.7                 | 49.3          | 14.2  | 2.2   |
| 2019  | Forch [118]     | 20–21 °C, 40% RH               | 35.8                 | 48.0          | 17.9  |       |
| 2019  | Meyland et al. [119] | 22 °C, 30% RH (as-received)   | 169.0                | 313.0         | 26.4^6 |       |
| 2020  | Brokmann et al. [195] | 25 °C, 30% RH (pre-damaged)  | 56.0                 | 88.0          | 34.6^6 |       |

* SCG = sub-critical crack growth.
* Estimated by means of least squares fit using Eq. (8).
* True fatigue parameter in parenthesis obtained by n' = 0.763 n, where n' is denoted the apparent fatigue parameter.
* True fatigue parameter in parenthesis obtained by n' = 0.75 n + 0.5, where n' is denoted the apparent fatigue parameter.
* True fatigue parameter in parenthesis obtained by n' = (3 n - 2)/4, where n' is denoted the apparent fatigue parameter.
* Averaged results determined by eight different laboratories.
* Only relative strength data are reported.
* Only the increase in strength as function of loading rate is reported and no absolute strength data are available.
References

[1] R.A. Behr, J.E. Minor, H.S. Norvile, Structural behavior of architectural laminated glass, J. Struct. Eng. 119 (1) (1993) 202–222, https://doi.org/10.1061/(ASCE)0733-9445(1993)119:1(202).

[2] J.E. Minor, H.S. Norville, Design of window glass for lateral pressures, J. Architect. Eng. 12 (3) (2006) 116–121, https://doi.org/10.1061/(ASCE)1076-0431(2006)12:3(116).

[3] R. Davies, N. Vigener, Architectural glass to resist snow loads, 9781845696395, in: R.A. Behr (Ed.), Archit. Glas. To Resist Seism. Extrem. Clim. Events, Elsevier, 2009, pp. 96–146, https://doi.org/10.1533/9781845696856.96.

[4] M. Badalassi, L. Biolzi, G. Royer-Carfagni, W. Salvatore, Safety factors for the structural design of glass, Construct. Build. Mater. 55 (2014) 114–127, https://doi.org/10.1016/j.conbuildmat.2014.01.005.

[5] C. Kameswara Rao, Safety of glass panels against wind loads, Eng. Struct. 6 (3) (1984) 232–254, https://doi.org/10.1016/0141-0296(84)90095-5.

[6] D.A. Reed, E. Simiu, Wind loading and strength of cladding glass, J. Struct. Eng. 110 (4) (1984) 715–729, https://doi.org/10.1061/(ASCE)0733-9445(1984)110:4(715).

[7] I. Calderone, W. Melbourne, The behaviour of glass under wind loading, J. Wind Eng. Ind. Aerod. 48 (1) (1993) 81–94, https://doi.org/10.1016/0167-6105(93)90282-S.

[8] I.J. Calderone, W.H. Melbourne, The equivalent wind load for design of glass in buildings, in: A. Jansen, G. Larose, F. Livesey (Eds.), Wind Eng. Ino 21st Century, A.A. Balkema Publishers, Rotterdam, Netherlands, 1999, pp. 1111–1115, 1-3.

[9] C. Barry, Architectural glass to resist wind pressures, 9781845693695, in: R.A. Behr (Ed.), Archit. Glas. To Resist Seism. Extrem. Clim. Events, Elsevier, 2009, pp. 169–192, https://doi.org/10.1533/9781845696856.169.

[10] T. Henriksen, S.O. Hansen, Design of glass for high, short duration wind loads, in: F. Bos, C. Louter, F. Veer (Eds.), Challenging Glass 2 - Conf. Archit. Struct. Appl. Glas., CGC 2010, May, TU Delft Open, 2010, pp. 629–637.

[11] E. Gavarnki, G.A. Kopp, Glass breakage tests under fluctuating wind loads, J. Architect. Eng. 17 (1) (2011) 34–41, https://doi.org/10.1061/(ASCE)AE.1943-5568.0000028.

[12] C. Pamejides, K. Truman, R. Behr, A. Belbari, Development of a loading history for seismic testing of architectural glass in a shop-front window system, Eng. Struct. 18 (12) (1996) 917–935, https://doi.org/10.1016/0141-0296(95)00224-3.

[13] R.A. Behr, Seismic performance of architectural glass in mid-rise curtain wall, J. Architect. Eng. 4 (3) (1998) 94–98, https://doi.org/10.1061/(ASCE)1076-0431(1998)4:3(94).

[14] T.J. Renick, R.A. Behr, Seismic performance of architectural glass in mid-rise curtain wall, J. Architect. Eng. 5 (3) (1999) 105–106, https://doi.org/10.1061/(ASCE)1076-0431(1999)5:3(105).

[15] R.A. Behr, Closure to “seismic performance of architectural glass in mid-rise curtain wall” by Richard A. Behr, J. Architect. Eng. 5 (3) (1999), https://doi.org/10.1061/(ASCE)1076-0431(1999)5:3(106)–106–106.

[16] A.M. Memari, R.A. Behr, P.A. Kremer, Seismic behavior of curtain walls containing insulating glass units, J. Architect. Eng. 9 (2) (2003) 70–85, https://doi.org/10.1061/(ASCE)1076-0431(2003)9:2(70).

[17] R.A. Behr, Design of architectural glazing to resist earthquakes, J. Architect. Eng. 12 (3) (2006) 122–128, https://doi.org/10.1061/(ASCE)1076-0431(2006)12:3(122).

[18] B. Huang, S. Chen, W. Lu, K.M. Mostalam, Seismic demand and experimental evaluation of the nonstructural building curtain wall: a review, Soil Dyn. Earthq. Eng. 100 (May) (2017) 16–33, https://doi.org/10.1016/j.soildyn.2017.05.025.

[19] W.L. Beason, G.E. Meyers, R.W. James, Hurricane related window glass damage in Houston, J. Struct. Eng. 110 (12) (1984) 2843–2857, https://doi.org/10.1061/(ASCE)0733-9445(1984)110:12(2843).

[20] K.C. Mehta, Wind induced damage observations and their implications for design practice, Eng. Struct. 6 (4) (1984) 242–247, https://doi.org/10.1016/0141-0296(84)90015-1.

[21] R.A. Behr, P.A. Kremer, Performance of laminated glass units under simulated windborne debris impacts, J. Architect. Eng. 2 (3) (1996) 95–99, https://doi.org/10.1061/(ASCE)1076-0431(1996)2:3(95).

[22] B. Hettis, Architectural glass to resist wind-borne debris impacts, in: R.A. Behr (Ed.), Archit. Glas. To Resist Seism. Extrem. Clim. Events, Elsevier, 2009, ISBN 9781845696856.169.

[23] R.A. Behr, Closure to “Seismic performance of architectural glass in mid-rise curtain wall” by Richard A. Behr, J. Architect. Eng. 5 (3) (1999), https://doi.org/10.1061/(ASCE)1076-0431(1999)5:3(106)–106–106.

[24] X. Zhang, H. Hao, G. Ma, Laboratory test and numerical simulation of laminated architectural laminated glass subjected to low velocity impacts from small rock fragments, J. Architect. Eng. 17 (1) (2011), https://doi.org/10.1533/9781845696856.193.

[25] F.J. Masters, K.R. Gorley, N. Shah, G. Fernandez, The vulnerability of residential window glass to lightweight windborne debris, Eng. Struct. 32 (4) (2010) 911–921, https://doi.org/10.1016/j.engstruct.2009.12.016.

[26] Z. Zhang, H. Hao, G. Ma, Laboratory test and numerical simulation of laminated glass window vulnerability to debris impact, Int. J. Impact Eng. 55 (2013) 49–62, https://doi.org/10.1016/j.impacteng.2013.01.002.

[27] F. Flocker, L. Dharani, Stresses in laminated glass subject to low velocity impact, Eng. Struct. 19 (10) (1997) 851–856, https://doi.org/10.1016/S0141-0296(97)00162-4.

[28] R.A. Behr, P.A. Kremer, L.R. Dharani, F.S. Ji, N.D. Kaiser, Dynamic strains in architectural laminated glass subjected to low velocity impacts from small rock fragments, J. Architect. Eng. 17 (1) (2011), https://doi.org/10.1533/9781845696856.193.

Data processed and indexed for DTU Findit are sourced from providers listed here: https://findit.dtu.dk/en/about/providers (retrieved: 28-01-2021).
M. Larcher, M. Arrigoni, C. Bedon, J.C.A.M. van Doormaal, C. Haberacker, X. Zhang, H. Hao, Z. Wang, Experimental study of laminated glass window
X. Zhang, H. Hao, Experimental and numerical study of boundary and anchorage effects of laminated glass in ballistic applications, Strain 50 (6) (2014) 470–500, https://doi.org/10.1177/1200589X14551313.
K. Osmen, D. Sey, O.S. Hopperstad, T. Bervik, On the dynamic response of laminated glass exposed to blast loading, Exp. Mech. 59 (7) (2019) 1033-1046, https://doi.org/10.1007/s11348-019-00946-1.
E.M. Pugh, R.V. Heine-Geldern, S. Fonar, E.C. Mutschler, Glass cracking caused by high explosives, J. Appl. Phys. 23 (1) (1952) 43–53, https://doi.org/10.1063/1.170977.
R.J. Harriss, M.R. Marshall, D.J. Moppett, Response of glass windows to explosion pressures, Int. Chem Eng Symm 49 (1977) 83–97.
D. Makovicka, P. Lexa, Dynamic response of window glass plates under explosion overpressure, in: P. Budon (Ed.), Under Shock Impact II, Computational Mechanics Publications Ltd, Southampton, 1992, pp. 381–392.
D. Makovicka, Shockwave load of window glass plate structure and hypothesis of its failure, in: N. Jones, D.G. Talalatisf, C.A. Brehbia, G.D. Manolios (Eds.), Struct. Under Shock Impact, Computational Mechanics Inc, 1996, pp. 43–52.
T. Krauthammer, A. Altenberg, Negative phase blast effects on glass panels, Int. J. Impact Eng. 24 (1) (2000) 1–17.
L. Dhariani, J. Wei, F. Ji, Failure analysis of laminated architectural glass panels subjected to blast loading, in: N. Jones, C. Brehbia, A. Rajendran (Eds.), Struct. Under Shock Impact VII, WIT Press, Southampton, UK, 2002, pp. 37–46.
L.R. Dhariani, J. Wei, Dynamic response of laminated glass under blast loading: effect of negative phase, in: N. Jones, C. Brehbia (Eds.), Struct. Under Shock Impact VIII, WIT Press, Southampton, UK, 2006, pp. 329-346.
K.A. Marchand, E.J. Conrath, D.J. Stevens, S.B. Meyer, Blast induced glass hazards: a comparison of design approaches and recent research, in: N. Jones, C. A. Brehbia (Eds.), Struct. Under Shock Impact IX, WIT Press, Southampton, UK, 2008, pp. 269-286.
J. Wei, M.S. Shetty, L.R. Dhariani, Failure analysis of architectural glass subjected to blast loading, Exp. Fail. Anal. 13 (7) (2006) 1029-1043, https://doi.org/10.1177/0890690506068807.
J. Wei, M.S. Shetty, L.R. Dhariani, Stress characteristics of a laminated architectural glass subjected to blast loading, Comput. Struct. 84 (10–11) (2006) 699–707, https://doi.org/10.1016/j.compstruct.2005.11.007.
P. Kumar, A. Shukla, Blast loading response of glass panels, in: P. Troids (Ed.), Conf. Proc. Proc. Exp. Mech. Ser. 17, vol. 6, Springer, New York, NY, 2011, pp. 131–132, https://doi.org/10.1007/978-1-4419-9792-0_21.
M. Larcher, M. Teich, N. Gebbeken, G. Solomos, F. Casadei, G.A. Falcon, et al., Dynamic response to the proportion of silica glass in ballistic applications, J. Mater. Sci. 34 (23) (1999) 5749–5756, https://doi.org/10.1023/A:1025030325816.
S.M. Walley, An introduction to the properties of silica glass in ballistic experiments and simulations, Int. J. Impact Eng. 88 (2016) 61, https://doi.org/10.1016/j.ijimpeng.2016.05.015.
