Engineering Structures 79 (2014) 96–105

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Size effect model for the edge strength of glass with cut and ground edge finishing

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ARTICLE INFO

Article history:
Received 17 January 2014
Revised 18 June 2014
Accepted 4 August 2014
Available online 24 August 2014

Keywords:
Structural glass
Edge strength
Size effect
Weibull distribution
Stress corrosion

ABSTRACT

The edge strength of glass is influenced by the size of the surface (near the edge) which is subjected to tensile stresses. To quantify this size effect, 8 series of single layer annealed glass beam specimens (as-received glass) were subjected to in-plane four-point bending with linearly increased loading until failure. Within the 8 series, the edge finishing differed between 'cut' and 'ground', the thickness between 4 and 8 mm and the beam length between 550 and 1100 mm. From the test results a reduction in strength was observed for increased specimen size, which is in line with common expectations. However, the analytical prediction of this reduction by probabilistic laws derived from the literature is unsafe. In fact, these predictions of the strength reduction were up to 14% less conservative than those observed from the presented test results. From this it is concluded that future standards should estimate the size effect more conservatively than currently done by the existing laws in the literature.

1. Introduction

In secondary construction elements such as windows, the edges are often subjected to considerable tensile stresses due to thermal actions. In addition, in structural glass applications, such as glass beams or glass façade mullions for which sometimes annealed glass is applied, the edges of the glass elements are subjected to significant tensile stresses. The edge strength values, given in existing standards [1–3] or in the literature [4–8] are based on testing. However, in the literature different testing methods with different specimen sizes are used, so a correct comparison of results is not always possible. Also, in the existing standard EN1288-1 [9], different methods are described. The most common test for determining the surface bending strength is the coaxial double ring test as described in EN1288-2:2000 [10]. In addition, EN1288-3:2000 [11] describes a four-point bending procedure to determine the strength of glass in out-of-plane bending (plates). For the assessment of the edge strength of beams this four-point bending procedure is commonly used, but in an in-plane bending configuration. According to [11], the load span should amount to 200 mm ± 1 mm. However, the edge of a glass beam in real-world applications often has a stressed length larger than 200 mm. Consequently, the test values have to be converted to be applicable for design. Due to an increased stressed area the probability of a more severe critical flaw increases, and thus the strength reduces [7,9]. Veer and Riemslag [7] conclude that this increased probability of critical flaws due to a size effect of the stressed area cannot fully explain the observed strength reduction. In the literature, formulas for this reduction are proposed [12–18]. However, in the existing standards [1,2], no reduction is mentioned. Only the standard NEN 2608 [3] proposes a reduction, applicable for the surface strength, as well as for the edge strength. Also, E2431-12 [19] provides a reduction applicable to the edge strength for the thermal breakage verification. Hence, a more rigorous study was deemed necessary.

In this study, 8 series of beam specimens, manufactured from as-received glass, with either cut or ground (without blank spots) edge finishing, a thickness of either 4 or 8 mm, and a length of either 550 or 1100 mm were tested in a four-point bending setup. As described above, the testing was performed with an in-plane bending setup as modified from standard EN1288-3:2000 [11]. All series were subjected to a linearly increased loading (constant stress rate) until failure.

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http://dx.doi.org/10.1016/j.engstruct.2014.08.004
0141-0296/

Nomenclature

a	correction factor (Hertzian line contact effect)
b	thickness of the specimen
b'	developed thickness of the specimen (see Fig. 3)
$b(n_S)$	the unbiasing factor for the Weibull shape parameter
c	sample coefficient of variation
d	distance between the load and the support
f	tensile strength corresponding to a constant stress rate
h	height of the specimen
m	the Weibull shape parameter
m_{corr}	the unbiased Weibull shape parameter
n	crack velocity parameter
n_S	number of strength values in a specific series
r^2	coefficient of determination (least-squares method)
s	sample standard deviation
t_f	time period during which the flaw can resist the stress history or time to failure
$\bar{x}$	sample mean value
A	the surface of the uniform loading
A_{test}	the surface of the uniform loading in the test setup
F_i	failure probability of the ith strength value
L	support span of the specimen
L_s	load span (stressed length)
L_t	specimen length
L_{small}	load span (stressed length) of the small specimens
L_{large}	load span (stressed length) of the large specimens
P	total load
P_f	experimental failure load
S	stressed surface
V	stressed volume
V_1	stressed volume of series 1
V_2	stressed volume of series 2
V_0	the unit volume
σ	maximum tensile stress, constant within the load span
σ_0	the Weibull scale parameter
$\sigma_{0,large}$	the Weibull scale parameter of the large specimen
$\sigma_{0,small}$	the Weibull scale parameter of the small specimen
σ_1	the Weibull scale parameter of series 1
σ_2	the Weibull scale parameter of series 2
σ_c	tensile strength corresponding to a constant stress rate, calculated by Eq. (1)
σ'_c	tensile strength corresponding to a constant stress rate, corrected for the Hertzian line contact effect
$\sigma'_{c,60}$	tensile strength corresponding to a reference period of 60 s, to a constant stress rate and corrected for the Hertzian line contact effect
σ_{ci}	tensile strength of the ith specimen of the series (corresponding to a constant stress rate)
σ_v	the Weibull scale parameter independent of the stressed volume

The objective of this investigation is to assess the strength reduction between the different beam sizes and to compare these experimental values with the probabilistic formulas available in the literature [12–18] and in the standards NEN 2608 [3] and E2431-12 [19].

2. Test specimens and method

For this research, single layer annealed soda lime silica glass panels of 1100 mm * 250 mm with a thickness of 4 or 8 mm and either simple cut or ground edges, were obtained from a qualified glass processor. The study was only performed with as-received glass, not with weathered glass or glass damaged during handling or transport or other in-service events that induce further flaws on the glass edge surface.

During the machine cutting and grinding of the panels a strict protocol was applied. More specifically, the scoring of the specimens consistently occurred at the air side (i.e. the surface which is exposed to the air (atmosphere) during the float process. Furthermore, the cutting wheel had an angle of 145° (pressure of 0.7 bar) for the 4 mm specimens and 154° (pressure of 1.8 bar) for the 8 mm specimens. In addition, for the ground specimens, the grinding was done with a diamond-grit wheel (D151, D91). The anris varied between 0.9 mm and 1.1 mm for the 4 mm thick specimens and between 1.2 mm and 1.4 mm for the 8 mm thick specimens (Figs. 3 and 5). Finally, per glass thickness (4 or 8 mm) and per edge finishing (cut or ground) all panels were processed on the same day with the same machine and the same processing parameters, from which one can assume the same flaw population between the series with small (length of 550 mm) and large specimens (length of 1100 mm). Subsequently, these panels were manually cut into 8 different specimen series with final nominal specimen dimensions of 550 mm * 62.5 mm or 1100 mm * 125 mm as indicated in Fig. 1. The specimens were cut such that the edge which was exposed to tensile stresses during the bending tests always corresponded to the machined cut or ground edge (instead

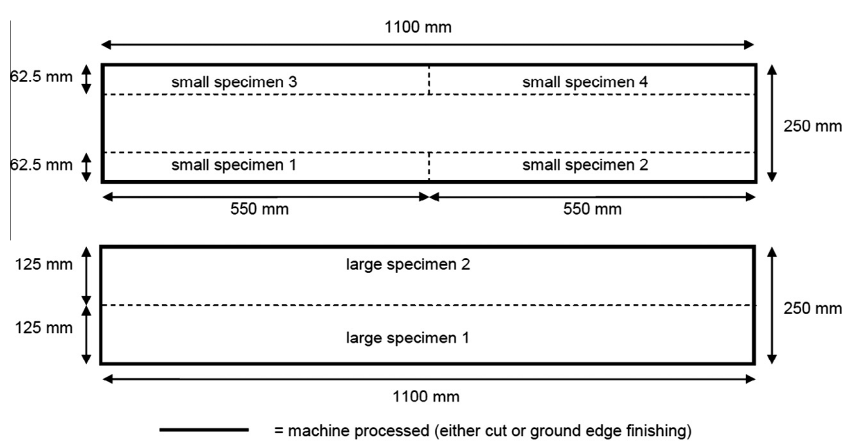

Fig. 1. Overview of the small specimens and the large specimens out of a large pane.