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WIRE GLASS IN BUILDING CONSTRUCTION

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Abstract: *Wire glass is frequently used in present-day building projects, not only as a filling material, but also for load-bearing members. Thus, there are the special requirements for glass, and it is necessary to assess the reliability of glass structures. In the framework of European standardization, there is not yet sufficient documentation for implementing standards for glass structures. However, a standardisation committee for structural glass has recently been established, and work is being done in this field. The present paper discusses use of the wire patterned glass and assessment of its design characteristics.*

Keywords: ***Wire glass, failure, strength.***

1. Introduction

Wire patterned glass is applied in a number of existing and new building structures. The wire mesh should prevent brittle failure and subsequent collapse of structural members. The design of a load-bearing member made of wire patterned glass should take into account actual properties of the material. Unrealistic design strengths have recently been published in the Czech Republic for wire patterned glass structures. This paper discusses the use of wire patterned glass, and proposes partial factors for glass strength based on previous experience and a limited amount of experimental data.

2. Wire glass

In this paper, wire glass refers to a normal glass which has a steel mesh inserted during the manufacturing process. This type of glass was often used in the past, when present-day requirements for the so-called safe glass were unattainable. Manufacturers formerly used the only available technology, which involved rolling the wire in the glass. When a glass panel is broken the mesh holds parts of the material together. However, this type of product cannot be considered as a safety glass, because the fragments are very sharp and dangerous.

Wire glass may fracture due to local non-homogeneities such as notches created when the glass is cut, and air cavities in the material formed when the wire mesh is embedded into the molten glass before rolling, initial corrosion of wires at edges of panels, etc. The strength of glass is also affected by climate effects. The effects of ageing reduce the critical stress intensity factor, and thus it is difficult to cut old glass even by diamonds.

Glass deforms proportionally to the load, and it breaks suddenly. It is a brittle material, and the failure occurs suddenly when the limit stress in tension is reached. The strength is usually determined as the flexural strength of glass, and is significantly variable. The coefficient of variation ranges from 15 to 30 %. The strength of glass depends significantly on its surface, defects, impurities and ambient moisture, Mencik (1990) and Volf (1984).

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The following standards are valid for the production of the wire glass:

- CSN EN 572-1 (2004) – determines the basic physical and mechanical properties of soda lime silicate glass (characteristic value of strength of glass without the embedded wire declared as 45 MPa),

- CSN EN 572-3 (2004) – specifies requirements for quality polished glass in terms of size and optical defects,

- CSN EN 572-6 (2004) – specifies the requirements for dimensions, including tolerances and permissible defects in wire patterned glass.

Traditional wire glass has been frequently used in building construction not only as a filling material, but often as a structural member that should meet safety requirements. In this case, it is necessary to supplement architectural design by reliability verification. The design of glass structures has often been based on long experience. With modern trends in architecture, the demands related to glass structures have been rising, but a design standard for structural glass is still missing.

Designers have access to some values of strengths given in available sources, but these values are not sufficiently specified, or may be completely unrealistic. Some sources provide values for the flexural strength of wire glass that corresponds to the strength of glass produced using modern technologies (up to 52 MPa). However, these values could have been hardly achieved using a traditional production technology.

A designer with insufficient experience and without detailed knowledge may then take these unverified material properties and design an unsafe structure (Fig. 1). Recently there has been an increasing number of problems associated with cracking or collapses of traditional wire glass. Accidents are very dangerous and not only pose a threat to life and health, but also lead to major financial losses. In most cases, structural members made from the wire glass are not properly statically assessed. Construction companies often employ craftsmen who have insufficient experience with the wire glass and poor assembly increases the frequency of failures.

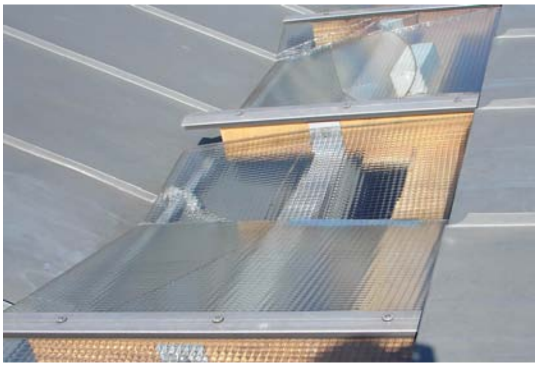

Fig. 1: Failure of wire glass caused by snow

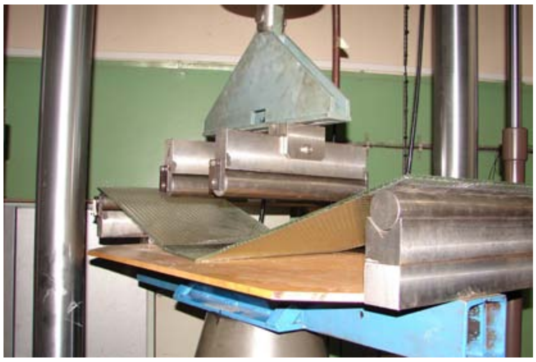

Fig. 2: Four point bending test on wire glass

3. Experimental determination of strength characteristics

The use of tests is an important aspect of ensuring the reliability of building structures, particularly when there are significant uncertainties about the material properties, as in the case of wire glass. No special standard is available for determining the tensile strength of this material.

Therefore, the standards for determining the flexural strength of monolithic glass for use in the construction industry have been applied for experimental determination of the flexural strength of wire glass. These standards can be used for establishing the equivalent strength, i.e. the apparent flexural strength of a glass in which irregularities in thickness do not permit a precise calculation of the normal stress.

The tensile strength of glass is influenced by the state of the surface, the rate of loading, the surrounding environment, the age of the glass, and temperature. According to CSN EN 1288-3 (2001), the dimensions of the glass specimen are 1100x360 mm, and the test is conducted as a four-pointed bending test for a span of 1000 mm. Three samples of wire glass specimens were tested in the CPU controlled hydraulic test machine. Before the test, specimens were weighed and their dimensions measured. Flexural tests must be carried out at a test facility that enables the specimen to be loaded with proportional loading with a limit error of ±2 % of the measurement range. The test (Fig. 2) has to be carried out in laboratory conditions.

4. Evaluation of the tests

Tests are usually evaluated using statistical methods. For conventional structural materials such as concrete and steel, the characteristic value of the material property is determined on the basis of tests, and the design value is determined using the partial safety factor. In the case of wire glass, however, there is no long-term experience and there are no recommended values for the partial factor. In this paper, the characteristic and design values of the wire glass strength are thus derived.

Three samples of the glass were tested in the laboratory of the Klokner Institute at the Czech Technical University in Prague.

A total of 31 tests were performed:

- 9 specimens provided by a manufacturer (*sample 1*),
- 10 specimens taken from a roof structure exposed to climatic effects (*sample 2*),
- 12 specimens stored in reserve for this roof structure (*sample 3*).

5. Strength of the wire glass

Sample 1 consists of specimens delivered directly from a manufacturer, so they do not include the effects of variability in strength among different batches nor climatic exposure. Specimens of nominal thickness of 6 mm fulfil the requirements according to the standard CSN EN 572-6 (2004). For *samples 2 and 3*, sufficiently large specimens were not available for the tests to be in full accordance with CSN EN 1288-1 (2001) and CSN EN 1288-3 (2001). The tests were performed on specimens with dimensions 150 x 800 mm supported in a span of 600 mm. The results of the tests may therefore be slightly affected by the smaller size of the specimens. However, this influence is assumed to be negligible.

The actual thickness shall be within a range of ±10 % (table 1 in CSN EN 572-3 (2004)) in the case of nominal thickness of 6 mm (*sample 1*) and 7 mm (*sample 2 and 3*). It is recommended to take the lower limit of tolerance into account when designing a structure.

Tab. 1 shows the statistical characteristics of *samples 1 to 3*. Apparently the mean value varies in a wide range from 31 to 40 MPa, and the coefficient of variation is in the interval 0.14 to 0.22. Fig. 3 presents a histogram and the probability density function of a lognormal distribution with the sample characteristics according to Tab. 1. Using standard statistical tests described e.g. by Vorlicek et al. (1982), no outliers were identified for all the *samples*.

Tab. 1: Statistical characteristics of samples 1 to 3

Sample characteristics	**Unit**	**Sample 1**	**Sample 2**	**Sample 3**
Number of samples n	-	9	10	12
Mean $m = \frac{1}{n}\sum_n f_i$	MPa	40.0	31.1	34.5
Coefficient of variation $V = s/m = \sqrt{\frac{1}{n-1}\sum_n (f_i - m)^2} / m$	-	0.22	0.22	0.14
Skewness $w = \frac{n}{(n-1)(n-2)s^3}\sum_n (f_i - m)^3$	-	0.77	0.95	0.75

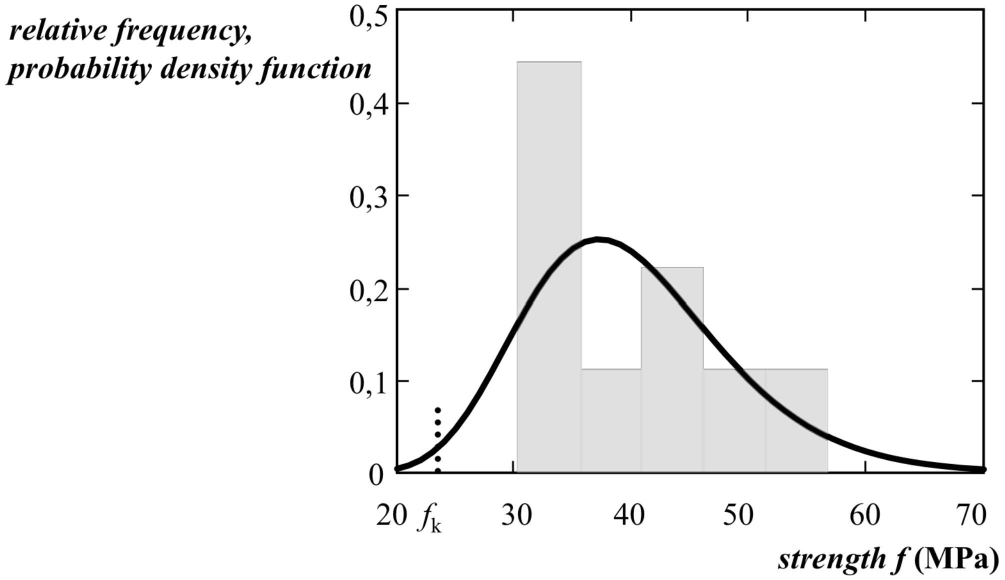

Fig. 3: Histogram and the probability density function of a lognormal distribution according to Tab. 1 for sample 1

6. Assessment of the characteristic value

Assessment of characteristic and design values of the strength of the wire glass is based on the method provided in Annex D to CSN EN 1990 (2011). This procedure assumes either normal or lognormal distribution of a construction material. In the following analysis the assumption of a lognormal distribution is accepted due to the following reasons:

- long-term experience with strengths of construction materials suggests a lognormal distribution,

- due to higher coefficients of variation of the glass strength (in comparison to steel and concrete) a normal distribution yields small or even negative values, which are unrealistic from the physical point of view,

- the skewness w of the *samples 1 to 3* (Tab. 4) is positive and relatively high, better corresponding to the skewness of a lognormal distribution ($w = 3V + V^3$) rather than to that of a symmetric normal distribution ($w = 0$).

CSN EN 1990 (2011) distinguishes between the two fundamental cases: the coefficient of variation of the strength population is "unknown" or "known". Due to the small sizes of all the *samples* taken from single production batches, the sample coefficient of variation is considered spurious. The long-term experience from a large number of tests in industrial production indicates that the coefficient of variation of glass commonly varies in the range of 0.15 to 0.3, Mencik (1990). Taking into account also experience from previous tests carried out in the Klokner Institute, a conservative coefficient of variation $V = 0.3$ is hereafter assumed to be “known”.

For a lognormal distribution, the characteristic value can be estimated as follows:

$$f_k = \exp[m_Y(1\text{-}k_n V_Y)] \quad (1)$$

where m_Y and V_Y are characteristics of the normally distributed variable $Y = \ln f$:

$$m_Y = (\Sigma_n \ln f_i) / n; \quad V_Y = \sqrt{[\ln(1 + V^2)]} / m_Y \quad (2)$$

The coefficient k_n can be either obtained from table D.1 in CSN EN 1990 (2011) or estimated by the following expression:

$$k_n(p) = -u_p\sqrt{(1 + 1 / n)} \quad (3)$$

where u_p is the fractile of the standardized normal variable corresponding to probability p. As an example $k_n(p = 0.05) = 1,73$ is obtained for $n = 9$ (*sample 1*). Estimated characteristic values are shown in Tab. 5. When a producer does not specify the characteristic value, it is highly recommended to determine f_k on the basis of tests.

7. Assessment of the design value and partial factor

According to relationships (6.6a,b) in CSN EN 1990 (2011), the design resistance R_d of a structural member can be determined from a general expression:

$$R_d = R(\eta_d f_k / \gamma_M, a_d) \tag{4}$$

where R(·) denotes the resistance function (e.g. the product of section modulus and the strength of the material), η_d is the design value of the conversion factor, and a_d is the design value of a geometrical property (e.g. the nominal width and thickness of the member reduced by the tolerance limit). The partial factor of material property γ_M, which takes into account model uncertainty and variability of dimensions, is determined from expression (6.6b) in CSN EN 1990 (2011):

$$\gamma_M = \gamma_{Rd}\, \gamma_m \tag{5}$$

where γ_{Rd} is the partial factor accounting for the uncertainty of the resistance model and the variability of dimensions, and γ_m is the partial factor for the material.

According to article 4.2(4)P in CSN EN 1990 (2011), it may be necessary to convert the test results to values representing the real behaviour of the material in a structure. The conversion factor η should then be used. For the wire glass, the conversion factor may account for the following influences that may affect structural members and are not included in laboratory tests:

- ageing,
- damage of a surface due to transport and assembly,
- size effects, etc.

A comparison of the mean values of *samples 2 and 3* (wire glass exposed to climatic effects, and wire glass without the exposure) shows decrease by about 10 %. In the absence of additional information the conversion factor η_d = 0,9 is considered taking into account a long-term experience with structural glass design. However, this assumption should be verified by further research.

For the wire glass, the model uncertainty factor γ_{Rd} should take into account the following:

- glass fracture usually occurs in places of local non-homogeneities (i.e. notches caused by glass cutting, air cavities due to a production process, wire corrosion at edges of a member progressing inward, see Figs. 4 to 6).

- actual thickness of the glass member is often lower than the nominal value.

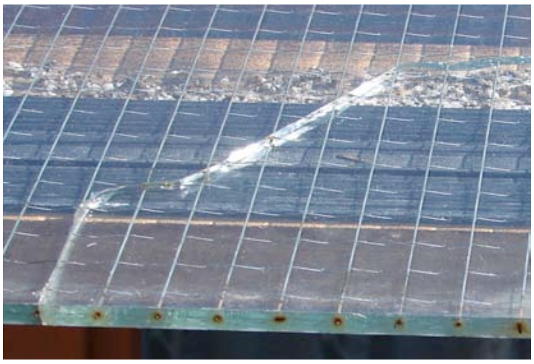

Fig. 4: Fracture due to corrosion of wires

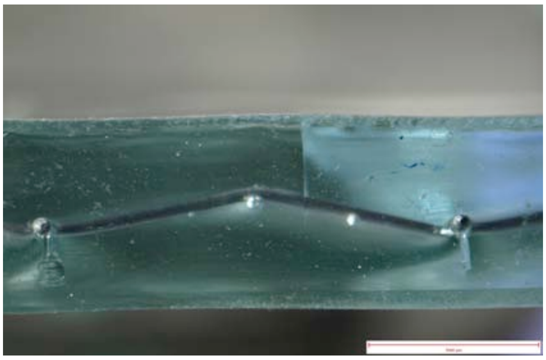

Fig.5: Notches caused by the cutting

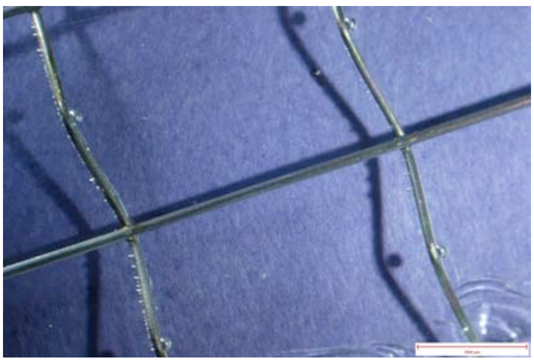

Fig. 6:Air cavities in glass

Report by fib SAG 9 (2010) indicates the model uncertainty factor for reinforced concrete members be usually $\gamma_{Rd} \sim 1,1$ to 1,15. For the wire glass, a larger model uncertainty is expected and $\gamma_{Rd} = 1,2$ is thus accepted. This assumption also needs to be further justified.

The partial factor for material property γ_m can be determined as follows:

$$\gamma_m = f_k / f_{pd} \quad (6)$$

where f_{pd} is the fractile of the strength corresponding to probability p_d (see relationship (C.6b) in CSN EN 1990 (2011)):

$$p_d = \Phi(-\alpha_R \beta) \quad (7)$$

where $\Phi(\cdot)$ denotes the cumulative distribution function of the standardised normal variable, $\alpha_R = 0,8$ is the sensitivity factor of the FORM method (CSN EN 1990 (2011)), and β is the target reliability index.

CSN EN 1990 (2011) gives minimum values of the reliability index β for the Ultimate Limit States (Tab. 2). Appropriate reliability class RC should be selected for a wire glass structure considering potential consequences of failure. Brittle failure of the wire glass is immediately followed by large deformations and displacements in mounting may lead to a sudden downfall of the wire glass panels. The collapse is not preceded by any warning such as development of cracks, sound effects or delaminating of surface layers. Therefore, it is recommended to consider RC3 for the wire glass structures where people gather, $\beta = 4,3$. Further information on selection of the target reliability index is provided e.g. by Holicky and Sykora (2012).

Tab. 2: Recommended minimum values of the reliability index β according to EN 1990 (Ultimate Limit States, reference period of 50 years)

Reliability class	**Consequence of failure**	**β**	**Examples of building or engineering structures**
RC3	High consequence for loss of human life, or economic, social or environmental consequences very great	4,3	Grandstands, public buildings where consequences of failure are high (e.g. a concert hall)
RC2	Medium consequence for loss of human life, economic, social or environmental consequences considerable	3,8	Residential and office buildings, public buildings where consequences of failure are medium (e.g. an office building)
RC1	Low consequence for loss of human life, and economic, social or environmental consequences small or negligible	3,3	Agricultural buildings where people do not normally enter (e.g. storage buildings), greenhouses

Tab. 3: Characteristic and design values and partial factors of the wire glass strength (samples 1 to 3)

	Unit	**Sample 1**	**Sample 2**	**Sample 3**
Characteristic value f_k	MPa	23,5	18,4	20,7
Partial factor γ_m	-			
RC1		1,36	1,36	1,36
RC2		1,54	1,54	1,53
RC3		1,74	1,74	1,73
Partial factor $\gamma_M = \gamma_{Rd}\,\gamma_m$	-			
RC1		1,63	1,63	1,63
RC2		1,85	1,84	1,84
RC3		2,09	2,09	2,08
Design value $f_d = \eta_d f_k / \gamma_M$	MPa			
RC1		13,0	11,3*	11,5
RC2		11,5	10,0*	10,1
RC3		10,1	8,8*	9,0

*$\eta_d = 1,0$ (panels tested after exposure to climatic effects)

Taking into account the target reliabilities according to Tab. 2, the probability p_d can be determined from Eq. (7):

$$p_d(RC1) = 0{,}0041;\ p_d(RC2) = 0{,}0012;\ p_d(RC3) = 0{,}00029 \quad (8)$$

These values can be substituted into Eq. (3), and for instance the coefficient $k_n(p = 0{,}00029) = 3{,}63$ is obtained for $n = 9$ (*sample 1*) and RC3. Then, the design value f_{pd} is determined from Eq. (1) and the partial factor γ_m from Eq. (6), see Tab. 3.

Partial factors γ_m obtained for *samples 1 to 3* and various reliability classes are given in Tab. 3. It appears that the partial factors γ_m for *samples 1 to 3* differ insignificantly which is attributed to the choice of the "known" coefficient of variation $V = 0{,}3$. As a first approximation partial factors γ_m can be estimated by the following values:

- $\gamma_m \approx 1{,}4$ for RC1,
- $\gamma_m \approx 1{,}6$ for RC2,
- $\gamma_m \approx 1{,}8$ for RC3.

Partial factors γ_M are determined using Eq. (5) and the design strength f_d is then obtained as follows:

$$f_d = \eta_d f_k / \gamma_M \quad (9)$$

For instance the design strength f_d varies from 9 up to 10 MPa for different samples and RC3.

8. Recommendations for practical applications

On the basis of long-term experience with the design of structural glass and evaluations of a limited number of tests, careful consideration of the following aspects is recommended in practical design of the wire glass:

1. tolerance of panel thickness (use of the lower limit of the tolerance interval is advised in common cases),
2. assessment of the characteristic value on the basis of tests unless specified by a producer,
3. account for influences likely affecting structural glass and hardly covered by laboratory tests (for example ageing, surface damage due to transport and assembly and size effect), using the conversion factor η,
4. application of the model uncertainty factor γ_{Rd} that if relevant, shall describe inaccuracy of the resistance models due to insufficient regard of the following factors:
   - fracture of the glass due to local non-homogeneities (notches, air cavities, wire corrosion).
   - thickness of the glass lower than the nominal value reduced by a tolerance limit, etc.
5. assessment of potential consequences of failure, and selection of an appropriate reliability class; when samples of the glass comply with the assumptions made in this paper (in particular $V < 0{,}3$), the following partial factors might be used:
   - $\gamma_m \approx 1{,}4$ for RC1,
   - $\gamma_m \approx 1{,}6$ for RC2,
   - $\gamma_m \approx 1{,}8$ for RC3,
6. when RC1 or RC3 is selected, the relevant partial factors γ_m given above should be applied in conjunction with the partial factors for permanent and variable actions γ_G and γ_Q adjusted for the relevant target reliability level. The adjustment should be, however, made in collaboration with qualified experts.
   Alternatively, it is possible to differentiate reliability in accordance with Annex B of CSN EN 1990 (2011) (clause B.3.3(1)) and modify partial factors γ_F only. In this case γ_m for RC2 is accepted and partial factors of unfavourable actions are multiplied by the factor K_{FI} (for instance $1{,}1\gamma_G$ and $1{,}1\gamma_Q$ are applied for unfavourable actions and RC3).

9. Materials alternative to the wire glass

Use of the wire glass in new building structures should be prevented since:

- strength of the wire glass is significantly lower than that of a safety glass,
- unlike safety glass the wire glass breaks into sharp fragments that may cause additional injuries.

Various types of the safety glass that may be used instead of the wire glass include a multi-layered laminated glass made from various films (for example polyvinylbutyral) or a single-layered glass.

10. Conclusions

Due to a production process a characteristic strength of the wire glass is significantly lower than the characteristic strength of the soda-lime-silicate glass declared in CSN EN 572-1 (2004) as 45 MPa. The design of structural wire glass should take into account local non-homogeneities and degradation effects. For structural members exposed to climatic effects use of modern safety glass is preferable.

Acknowledgement

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