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OPTIMISING CONNECTIONS IN STRUCTURAL GLASS

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ABSTRACT

Three main considerations when designing structural glass assemblies are performance, appearance and economy. In point-supported structural glass these requirements are generally determined by the form and position of the connections. To date, extensive prototype testing has been the favoured method for predicting the strength of structural glass connections. The cost and time associated with such testing limits the amount of shape, size and material permutations and thus makes the optimisation of connections prohibitively expensive.

A simple yet accurate computer algorithm for predicting the strength of glass connections is put forward in this paper. This algorithm takes into account the factors that are known to affect the strength of annealed, heat-strengthened and toughened glass. The proposed computer algorithm and the associated finite element analysis are used to analyse conventional connections and subsequently to optimise these connections by varying both the geometry of the connection and the materials used.

The analytical results and initial experimental investigations of the conventional connections show that the proposed computer algorithm is able to predict the strength of a variety of connections with a good degree of accuracy and to optimise the geometry of bolted connections. The on-going and future applications of this algorithm are also discussed.

INTRODUCTION

Structural optimisation is the use of mathematical techniques to obtain the most economical design for a given structure. The primary aim of optimisation is to determine the design variables within the set constraints in order to give the minimum weight or cost. The application of this technique in the building industry is still in its infancy and is not yet sufficiently developed to be used in mainstream structural engineering design. However individual elements such as plate girders and trussed may be optimised with relative ease.

The past 25 years has seen an increasing architectural trend for maximum transparency of facades with minimum supports. This trend has generated various point-support systems in which the glass panels are supported close to their corners (Figure 1 & 2) and suspended from cable trusses or glass fins positioned behind the glass façade. These high performance facades may cost in excess of £1000 per square metre. This relatively high cost makes optimisation an attractive and highly beneficial exercise.

The accurate design of these complex facades is generally beyond the capabilities of the design recommendations originally developed for the two and four edge support conditions and normally require finite element analysis and extensive prototype testing.

However, recent research has given us a much better understanding of the strength and failure mechanisms of glass [Beason & Morgan (1984), Sedlacek *et al.* (1995), Fischer-Cripps & Collins (1995), Overend *et. al.* (1999), Porter & Houlsby (2001) and Overend (2002)]. From this research there is a general agreement that the maximum stress oriented theories cannot portray the strength of glass accurately. Instead the strength of glass is related to factors that affect the surface characteristics of glass such as load duration, surface area, environmental conditions, magnitude of surface stresses and distribution of surface stresses. These considerations form the basis of the design methodology proposed in the draft European Standard for the design of glass panes [CEN/TC129 (1999)]

Furthermore, the little published research available on the strength of bolted connections in glass confirms that the load bearing capacity of façade systems is often limited by the high stresses around the bolt holes [Overend (1996), Ramm & Burmeister (1997) and Baldacchino (1999)].

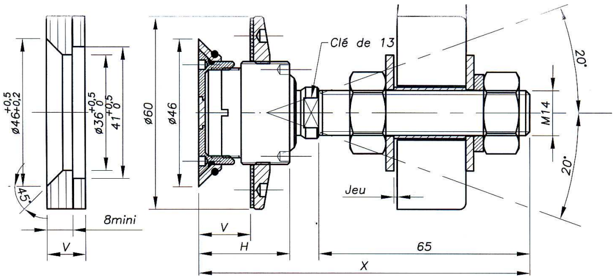


Figure 1 Articulated point fixing courtesy of Sadev

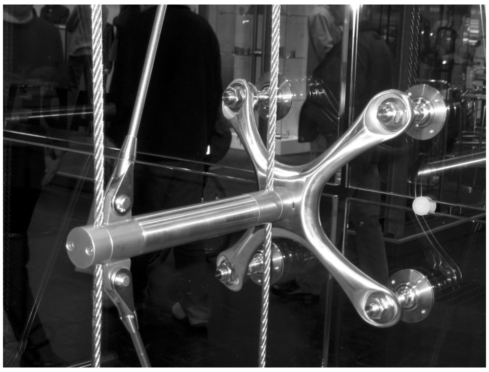


Figure 2 Undercut point fixing courtesy of FEV Italia

A computer algorithm for determining the strength of glass was recently developed by the author [Overend (2002)]. This algorithm makes use of the results obtained from finite element analysis to accurately predict the strength of glass without the need for unattractive manual calculations or expensive prototype testing. With the increasing power of computers, this algorithm may also be used within optimisation routines for structural glass connections.

This paper describes the basis of the underlying glass failure prediction model and the formulation of the computer algorithm. This paper also describes the numerical investigations carried out to optimise typical bolted connections.

TENSILE STRENGTH OF GLASS

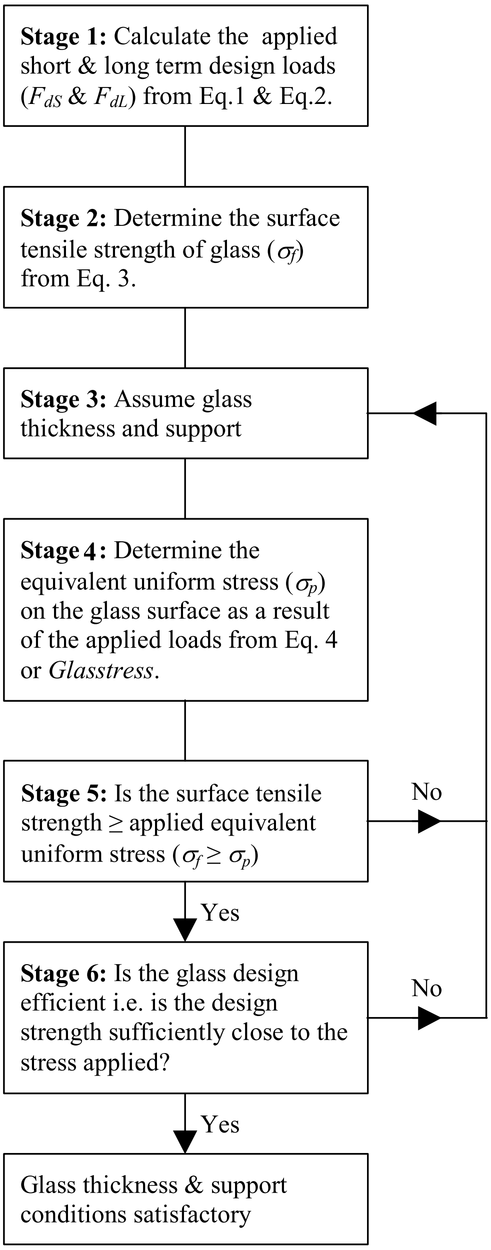
The transparency of glass is a result of its manufacturing process where the constituent materials are heated to form a viscous magma that is subsequently cooled on the float bath before it can crystallise. The resulting random molecular structure lacks long-range order and has no slip planes or dislocations to allow yield before failure. Consequently glass should exhibit a brittle fracture at a theoretical value of 21,000N/mm^2. However, fracture does not start from a pristine surface, but from Griffith flaws that exist on the surface of the glass. These flaws are atomically sharp therefore causing the glass to fail at much lower tensile stresses. For example the draft European Standard [CEN/TC129 (1999)] proposes a value of 45N/mm^2 for its unfactored mean strength and the strength of glass subjected to long-term stresses may be as low as 8N/mm^2 [Pilkington Glass Consultants (1997); Institution of Structural Engineers (2000)]. Furthermore, the random size, position and orientation of the Griffith flaws also cause a wide variability in the strength data of nominally identical specimens.

Despite these factors, traditional glass design procedures have historically relied on the empirical representations of glass strength and rules of thumb. These empirical rules have stood the test of time because glass was predominately used in short span window-infill applications. However, with the development of the curtain wall glass has evolved into a more important structural component of the building envelope. These developments led the glass design community to propose the first analytically derived failure prediction models for glass [Beason & Morgan (1984)]. From the various numerical and physical tests carried out [Beason & Morgan (1984), Charles (1958), Brown (1974), Dalgliesh & Taylor (1990) and Norville et al (1991)], it may be concluded that the strength of glass depends on the following parameters:

(i) load duration.
(ii) surface area of glass exposed to the tensile stress.
(iii) environmental conditions, especially humidity.
(iv) magnitude and distribution of load-induced surface tensile stresses in glass.
(v) ratio of major and minor principal tensile stresses on the surface of the glass.

More recently, a number of crack growth models have emerged as the most accurate representation of glass failure and strength [Sedlacek et al. (1995), Fischer-Cripps & Collins (1995), Porter & Houlsby (2001)]. These models have been developed in response to the growing structural role of glass and were derived from the application of linear elastic fracture mechanics. However, despite their improved accuracy these models are inherently unattractive for manual computation.

The design methodology adopted in this paper is based on the above-mentioned crack growth models and is summarised in Figure 3.



$$F_{dS} = \sum \gamma_G G_k + \gamma_Q Q_{kLT} + \gamma_Q Q_{kST} \qquad (1)$$

$$F_{dL} = \sum \gamma_G G_k + \gamma_Q Q_{kLT} \qquad (2)$$

$$\sigma_f = k_{\text{mod}} \sigma_s + \sigma_r / \gamma_v \qquad (3)$$

$$\sigma_p = \left[\frac{1}{A} \int_{area} \left(c_b \sigma_{\max} \right)^m dA \right]^{1/m} \qquad (4)$$

	Notation
A	surface area
c_b	biaxial stress correction factor
F_{DL}	long-term design loads
F_{DS}	short-term design loads
G_k	Dead loads
k_{mod}	stress corrosion ratio
m	surface strength parameter
Q_{kLT}	Long-term unfactored imposed load
Q_{kST}	Short-term unfactored imposed load
γ_g	partial safety factor for dead loads
γ_v	material safety factor for tempered glass
γ_q	partial safety factor for imposed loads
σ_{max}	major principal stress
σ_{min}	minor principal stress
σ_f	surface tensile strength of glass
σ_p	equivalent uniform stress
σ_r	surface pre-compression due to tempering

Figure 3 Outline flowchart for the structural design of glass (ultimate limit state)

All stages of this design methodology, with the exception of stage 4, are very simple to compute manually. Stage 4 involves the subdividing the surface area of the plate into areas of comparable major principal tensile stress σ_{max} . For each area *i* the relative contribution to the probability of failure is determined from $\left(c_{bi}\sigma_{\max i}\right)^m A_i$. The equivalent uniform stress over the whole surface area σ_p is the summation of the contributions of all the areas. Furthermore, the accuracy of this method is directly related to the variation of σ_{max} within the arbitrary subdivisions *dA* set out in Equation 4. The increased density of subdivisions will therefore increase the accuracy but make the method even less attractive for manual computation.

The alternative conservative approach is to assume that the whole of the glass surface is subjected to the major principal stress i.e. $\sigma_p = \sigma_{max}$. This results in a safe yet inefficient design particularly where steep stress gradients exist across the surface of the plate such as encountered in point supported glass plates. A computer algorithm was therefore developed by the author to automate the computation of stage 4 in the design methodology.

FORMULATION OF THE COMPUTER ALGORITHM

The computer algorithm is written in Visual Basic Computer Language and automatically computes the equivalent uniform stress, σ_p. The effectiveness of the algorithm is that it works off the results of Finite Element (FE) Analysis. The algorithm is run within the post-processor of commercially available FE analysis software packages or may alternatively be adapted to run independently and access the FE results files where required.

Interactive input to the computer consists of the co-ordinates of the surfaces to be analysed and the magnitude of surface pre-compression, σ_r, due to the toughening process ($\sigma_r = 0$ for annealed glass). The algorithm uses the FE mesh as the subdivisions to calculate the areas *dA* and automatically averages the principal tensile stress, σ_{max} within each element of the FE model. The equivalent uniform stress, σ_p, for the whole surface is subsequently summated automatically in accordance with Equation 4. The algorithm also creates a spreadsheet containing a detailed breakdown of these calculations and a summary of the entire surface analysed. The algorithm is capable of handling a variety of commonly used elements ranging from 3-noded triangular elements to 20-noded brick elements.

The equivalent uniform stress, σ_p, obtained from this computer algorithm may be used to verify the structural adequacy of the glass element by comparing it to the tensile strength of glass [Overend & Parke (2002)]. The equivalent uniform stress may also be used as the design variable for optimisation.

PARAMETRIC OPTIMISATION OF BOLTED CONNECTIONS

The use of the computer algorithm was initially verified by assessing its ability to predict the failure load of laterally loaded rectangular glass testing carried out by other investigators. The predictions obtained from the proposed algorithm produced a substantially closer prediction of failure than those obtained from the maximum stress approach [Overend (2002)].

The use of this algorithm was subsequently extended to the optimisation of bolted connections by carrying out a parametric study of the various factors that affect the strength of these connections. The FE analysis was carried out on Lusas version 13. The design variables investigated were:

(i) Shape of bolt and hole (k_{shape}).
(ii) Closeness of fit (k_{fit}).
(iii) Ratio of hole diameter and end distance to width of plate ($k_{edge/end}$).
(iv) Modulus of elasticity of liner (k_{liner}).

Preliminary FE analysis was carried out on a simple pin and lug model to identify a mesh density, mesh type and nonlinear analysis control parameters that would minimise modelling errors and ensure convergence. The results obtained from this preliminary analysis were within ± 3% of the theoretical results reported in Pilkey (1997).

Analysis of shape of bolt and bolt-hole

The aim of the first set of FE models constructed was to quantify the k_{shape} term by comparing the commonly used countersunk bolt (Figure 4a) to the standard double shear through bolt (Figure 4b) and to quantify the effect of pin-to-hole clearance and type of liner on the stress distribution. To this end, the performance of two commonly used liners (nylon and aluminium) was investigated and four pin-to-hole clearances ranging from a snug fit of 0.2% to a very loose fit of 10% were analysed.

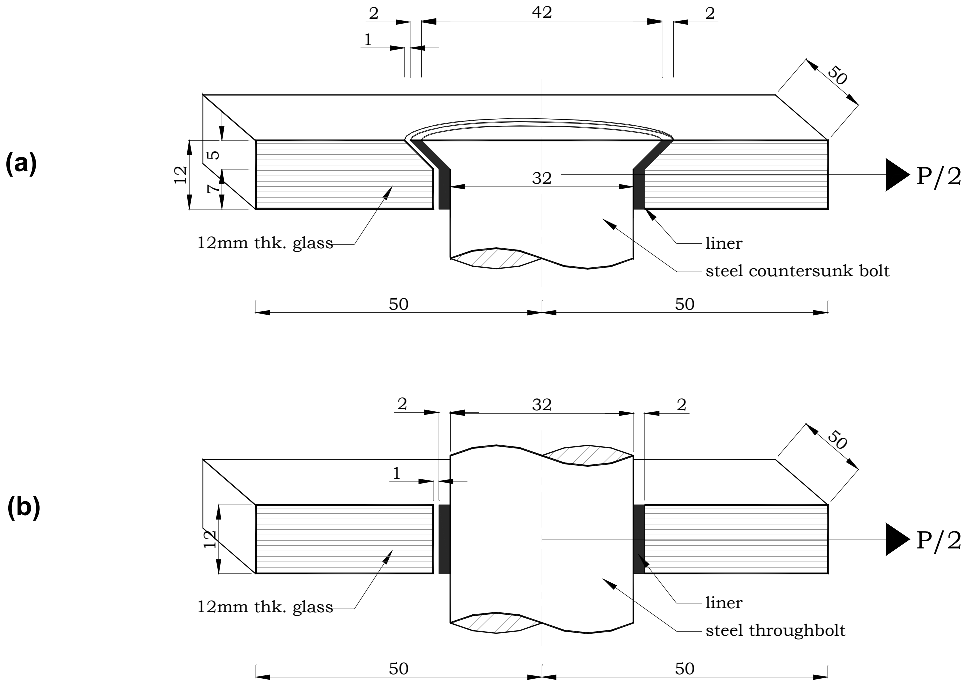


Figure 4 Bolted connections
Dimensions used for FE modelling of (a) countersunk bolt and (b) through bolt connection both of which make use of 1/4th symmetry.

Results for shape of bolt and bolt-hole investigations

The FE analysis results of the through-bolt and the countersunk bolt, shown in Figure 5, indicate that the countersunk bolt causes an uneven stress distribution across the thickness of the glass. The maximum principal tensile stress at the shank position of the countersunk bolt is 13% higher than the maximum principal tensile stress at the countersunk head and approximately 2% higher than that imposed by the through bolt.

The mechanical properties of the liners used seem to have a negligible effect on the magnitude of the maximum tensile stresses. The main advantage of using the softer nylon liner is the substantial reduction and better distribution of the bearing compressive stress.

The effect of bolt-to-hole clearance, *e*, on the major principal stress distribution is shown in Figure 6. The clearances investigated range from a snug fit of 0.2% to a very loose fit of 10%.

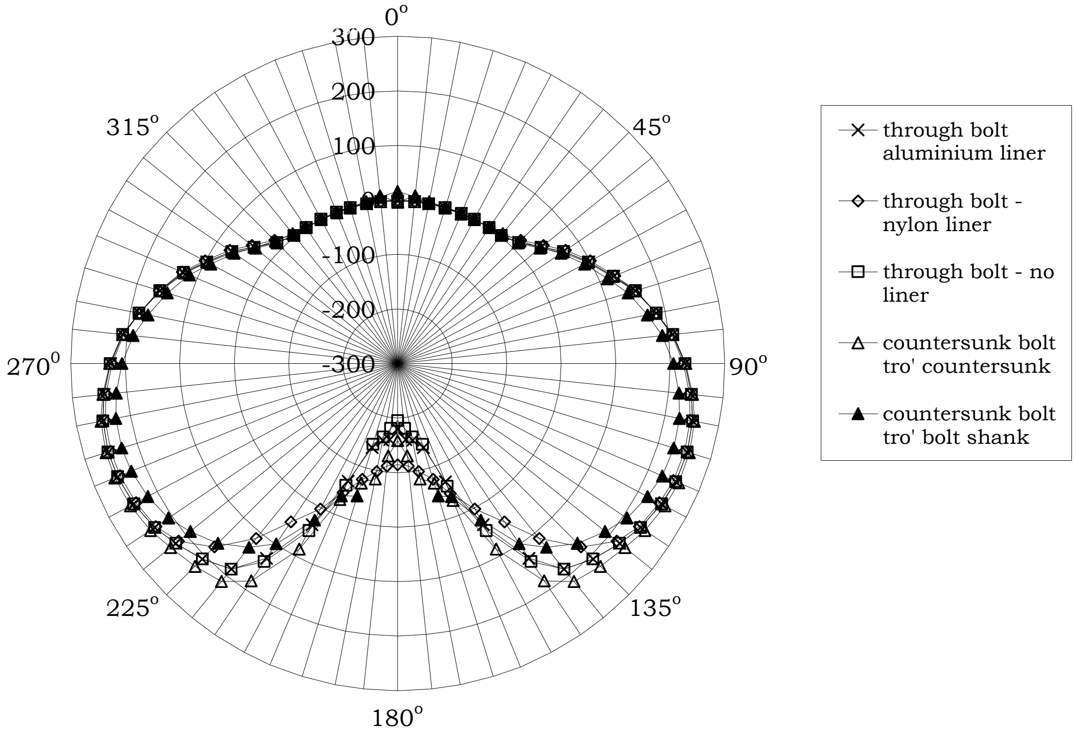


Figure 5 Stresses around bolt-hole perimeter
Major principal stresses around the bolt-hole for the 32mm diameter countersunk bolt with no liner and the 32mm diameter through bolt with no liner, nylon liner and aluminium liners.

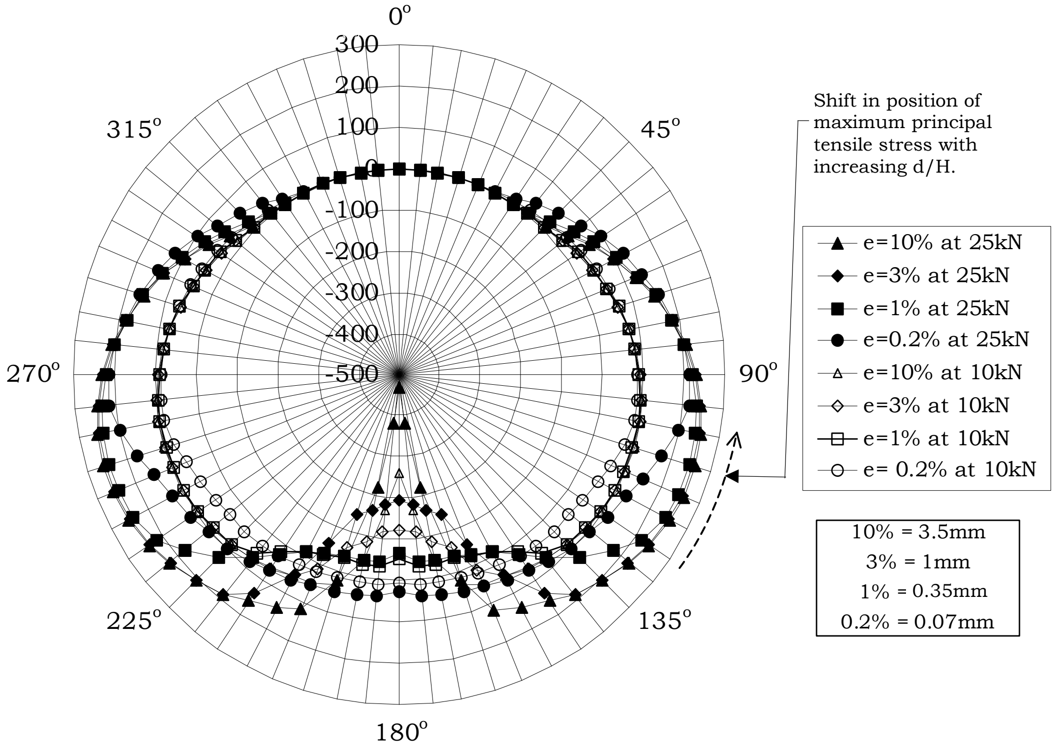
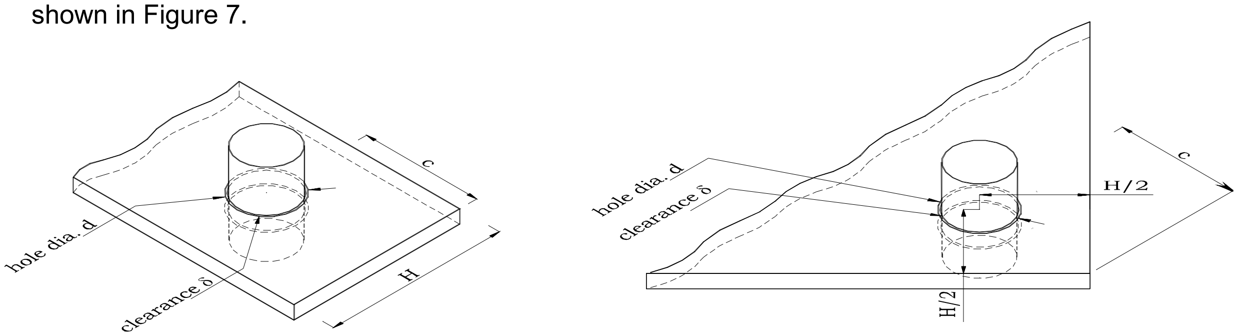


Figure 6 Stresses around bolt hole perimeter with varying tolerances
Major principal stresses for 32mm diameter through bolt with varying tolerances, *e*, as a ratio of hole diameter, *d*, at 10kN and 25kN.

The smaller tolerances of 3%, 1% and 0.2% produce a principal tensile stress that is 98%, 94% and 83% respectively of the principal stress from a 10% clearance. However, the main advantage of adopting a smaller clearance is the substantial reduction in compressive stress at the bearing end of the hole. It is also interesting to note that a tighter fit causes the maximum principal tensile stress position to shift away from the direction of the applied load.

Analysis of edge and end distances

Numerical investigations were carried out to quantify the effects of edge and end distances, as well as glass plate termination details on the resulting major principal stress distribution. These effects represented by the $k_{edge/end}$ term. were performed for the through-bolted connections shown in Figure 7.



(a) **(b)**

Figure 7 Geometry of bolted connections
Geometry of bolted connections used to determine edge and end effects of (a) edge connection and (b) corner connection.

The standard 2D FE model of the double-shear bolted connections was modified geometrically to result in the array of end distance/plate width ratios, c/H, and hole diameters, d, shown in Table 1. The closeness of fit, *e* was kept constant at 3% all runs.

Table 1 FE analysis for edge and end investigations

c/H	Type	Hole diameter d (mm) - Bolted connections	Coin Diameter d (mm) - Adhesive connections
50/100	edge	25, 35, 45, 60, 80	35, 60
100/150	edge	25, 35, 45, 60, 80	25, 35, 45, 60, 80
100/100	edge	25, 35, 45, 60, 80	35, 60
100/500	edge	35, 45, 60, 80, 100	35, 60
50/71	corner	25, 35, 45, 60, 80	35, 60
100/141	corner	25, 35, 45, 60, 80	35, 60

Results for edge and end distances investigations

The resulting radar graph (Figure 8) indicates that a reduction in edge and end distances produces an increase in maximum principal tensile stresses. A similar increase in tensile stresses also occurs when the bolt-hole diameter is decreased. However when the edge distance and the bolt-hole diameter are of comparable size, increasing the bolt hole diameter may be counter productive due to the reduction in glass cross-sectional area.

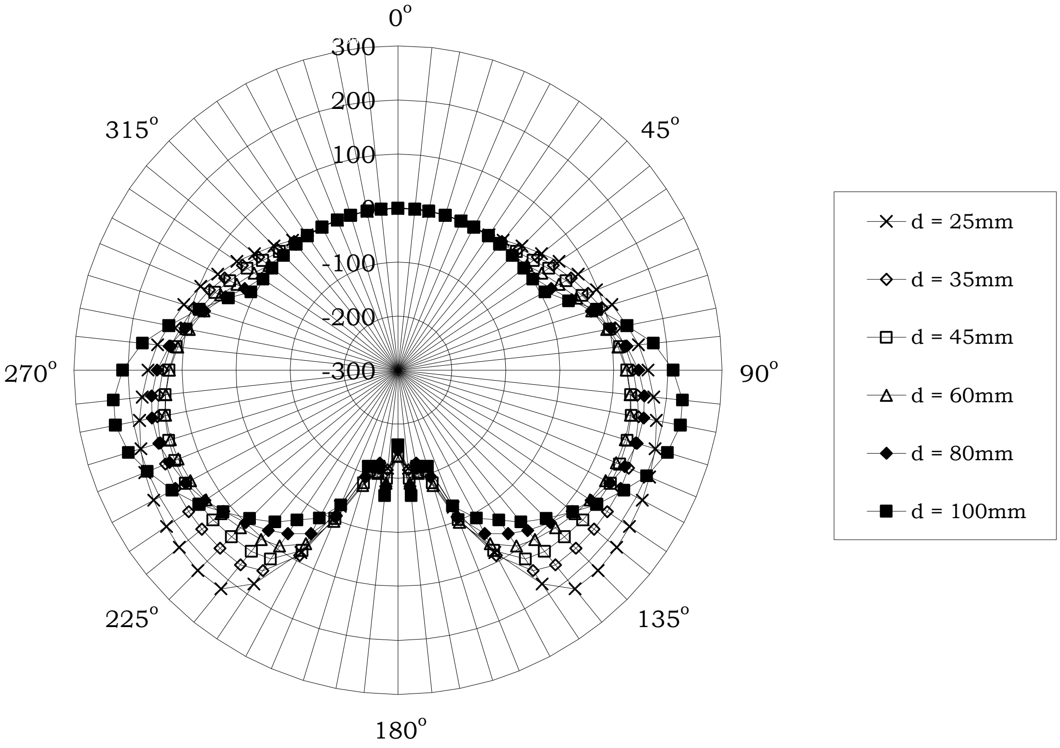


Figure 8 Stresses around bolt hole/adhesive perimeter
Major principal tensile stresses for through-bolted connections with square edge glass plate and c/H = 100/150.

It is also interesting to note that by increasing d/H the position of the maximum principal tensile stresses shifts towards a position which is perpendicular to the applied load (Figure 8).

From the variation of the peak stresses for varying diameters and different c/H ratios shown in Figure 9, it is apparent that an optimum hole diameter exists for a given edge and end distance.

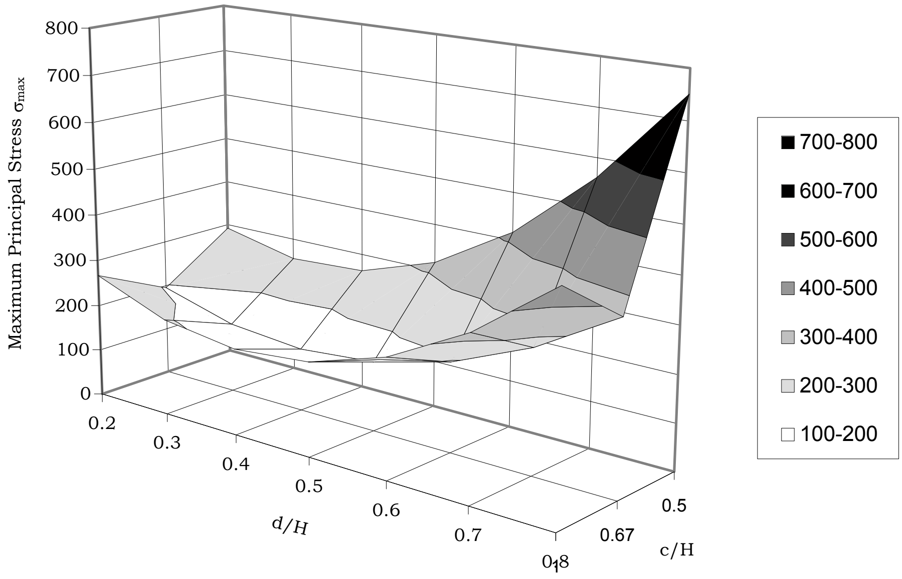


Figure 9 Peak tensile stresses for various d/H and c/H ratios with a 25kN load.

Application of computer algorithm

The comparisons carried out so far are based on the comparison of the maximum principal tensile stress. These comparisons are generally useful for assessing the approximate relative efficiency of bolted connections. However, since the strength of glass is based on a weighted average of all the surface tensile stresses, such comparisons do not provide accurate predictions of the strength of these connections.

The computer algorithm, described earlier in this paper, was therefore used to calculate the equivalent uniform stress, σ_p, which is a direct measure of the efficiency of the connection (Figure 10). The most efficient connection would be one that distributes the load uniformly over the surface of the glass plate thus utilising the full strength of the glass. In this case the equivalent uniform stress would be 27.7 N/mm^2.

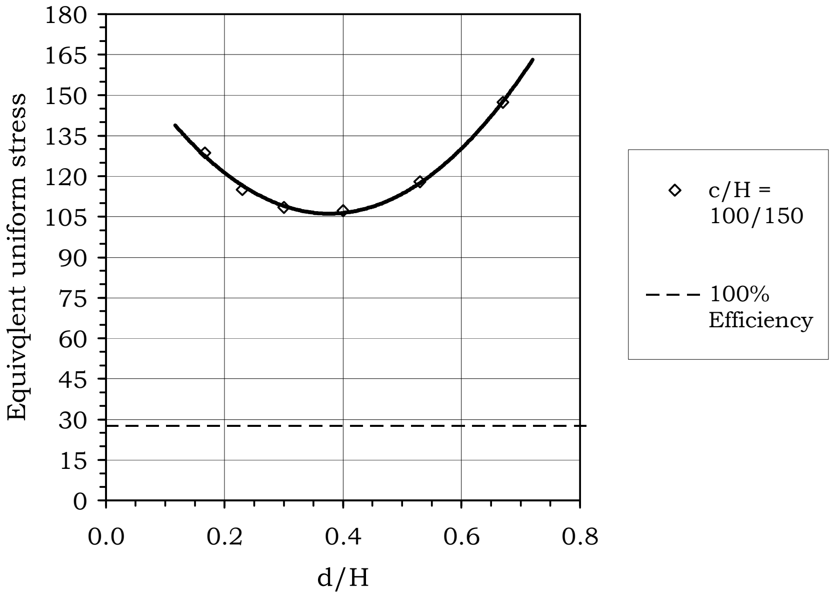


Figure 10 Equivalent uniform stress
Variation of equivalent uniform σ_p for bolted connection with square edge and c/H = 100/150.

CONCLUSION AND ON-GOING INVESTIGATIONS

The design methodology and the computer algorithm presented in this paper provide an accurate and economic way for optimising structural connections in glass.

For the bolted connections discussed in this paper, the tight-fit through bolt with a nylon liner results in the lowest major principal tensile stress. The optimum hole diameter was found to be a function of the end and edge distances. For a *c/H* = 100/150, the optimum hole diameter was found to be approximately 60mm. Furthermore, the most efficient bolted connection discussed in this paper results in an equivalent uniform stress, σ_p, of 106N/mm^2. Such a connection is relatively inefficient as it is utilising only 26% of the possible strength of glass.

Initial experimental investigations on bolted connections indicate that the proposed design methodology and computer algorithm are able to predict failure with a high degree of accuracy. Further experimental investigations are currently being planned to devise more efficient connections and to extend the computer algorithm to laminated glass.

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