

# Glass Footbridge



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**Abstract** When a footbridge is made of glass, it shows to the pedestrians the wonder and uniqueness of itself, i.e., its transparent characteristic. However, the perceived unwanted characteristics, such as the brittleness of glass may make it unsuitable, if used for a load-bearing structural member. But, using a toughened and laminated glass panel as the primary structural member can be practical because this toughened glass has a higher failure strength and is considerably safer when compared to ordinary glass. This paper began with an architectural drawing of a glass footbridge. Each primary beam of the footbridge was made from a large-sized glass panel. The bridge was modeled using beam finite elements and analysed using the finite element program, SAP 2000. The model was initially formed in 2D and analysed using two different support conditions. The analysis was repeated for a 3D model. The results of maximum moments, shear forces and deflections produced using both the 2D and 3D models and also using different support conditions are compared. The maximum stress was calculated and checked with the failure strength of toughened glass. The maximum deflection was also checked with the limiting value given in standard codes of practice. Connectors have been designed to connect the glass sub-panels together which have been used to form the large size glass panels, namely, the primary beams. The connectors have been designed and the stress level in the connection checked. Modal analyses using 2D and 3D models were also carried out to give frequencies and mode shapes of the footbridge under vibration. The frequencies are checked against the minimum value required

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according to standard codes of practice. All of the above checks were found to satisfy the relevant design criteria, and consequently the footbridge is now considered to be safe and ready for construction.

**Keywords** Glass footbridge · Finite element · SAP2000

## 1 Introduction

Over the last years, architects and interior designers have been busy creating new innovative structural designs using new types of materials. Laminated glass has driven a growing number of architects and engineers to work with elements in unconventional ways. To exploit the unique characteristics of glass, it should be used as the structural material for a closed room which will allow the sun, moon, and stars to be viewed, while protecting the room from rain, wind and cold, which is only becomes possible by using structural glass. In this paper, a footbridge made from glass was investigated. The idea came from an architectural drawing by an architect named Joris Luchinger, which is displayed in Nijssse [1]. The property of transparency is a valued feature in this glass footbridge.

It certainly takes a leap of faith to cross a glass footbridge where there is no visible framing, but which is only made of toughened laminated glass panels supported by toughened laminated glass beams. So far, only a small number of designers are willing to participate in using glass as the structural material because of its unpredictability and potential to injure people in the case of a breakage or falling shards. Glass acts in a significantly diverse manner compared to other materials like, for example, steel. The failure of an annealed glass beam is brittle, unlike a steel beam which may fail exhibiting large deformations. If an annealed glass beam is over loaded it would fracture and break completely, thus causing sudden failure of the beam. However, recent use of glass as a structural material has not only given us great exposure but has helped people realize that laminated glass can be used safely and successfully in working situations as proven by certain architects and engineers, where three panels of glass glued together can make a safe structural beam element.

As engineers, our paramount responsibility is the safety of people using the structure. An engineer naturally has to assume the obligation to analyse all possibilities of unwelcome effects of the proposed innovation. In this study, as mentioned above, a study of the behavior of the proposed glass footbridge structure drawn by Joris Luchinger (Nijssse 2002) was investigated. From a model analysis, the maximum moment, shear force, deflection and stresses of the glass panels were obtained. Then a modal analysis was conducted in order to obtain frequencies and mode shapes of the glass footbridge model. The model was created in the form of 2D and 3D to investigate the behavior of the proposed glass footbridge and also to have a comparison between the two models. However, in the 2D analysis, horizontal and torsional mode shapes are restricted which can only be obtained from a

3D analysis. Since the bridge has not been constructed and only a detail architectural drawing was given, a model and linear elastic analysis of this glass footbridge was undertaken in order to determine the behavior of the proposed glass footbridge structure.

### 1.1 Strength of Glass

Generally, loading on a structure induces bending moments and shear forces in the structural members. The bending moments are analysed and assessed. In order that the benefits of the analysis can be realized, the values of the bending moments must be used to check the stress levels developed in the members subjected to the load. Hence, a check for safety on the value of the maximum bending stress initiated from the maximum bending moment value used on the basis of factored loading not exceed the design stress.

For a structure made of glass, the undesirable characteristics of this material, i.e., its brittle character can cause fracture especially where there are flaws on the surface of the glass which normally leads to stress concentrations. Hence, the possibility of the formation of stress concentration cannot be overlooked and must be considered in the design procedure whenever glass is used. Table 1 shows the design stresses of different types of glass, such as float glass, heat-strengthened glass and toughened glass. The values of the design stresses are for use with factored loads and, where appropriate, for nonlinear analysis. In this paper, toughened glass is used and therefore the maximum bending stress value obtained from the glass footbridge analysis were compared with the design stress/strength of toughened glass given in Table 1.

**Table 1** Design stresses (Concept Ritchlijn: Construction glass (Holland), October 1996)

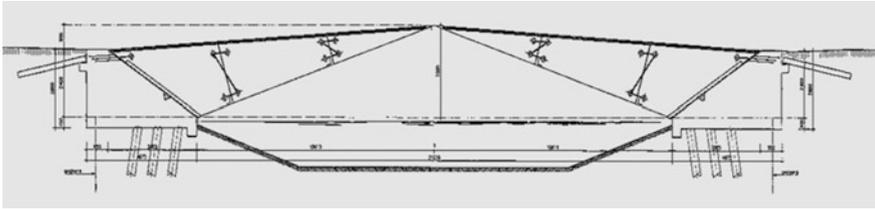
Type of glass	Permanent loads	Medium-term loads	Short-term (gust) loads
Float glass	7 N/mm <sup>2</sup> -single	17 N/mm <sup>2</sup> -single	28 N/mm <sup>2</sup> -single
	7 N/mm <sup>2</sup> -single	14 N/mm <sup>2</sup> -double	24 N/mm <sup>2</sup> -double
Heat-strengthened glass	22 N/mm <sup>2</sup> -single	24 N/mm <sup>2</sup> -single	37 N/mm <sup>2</sup> -single
	19 N/mm <sup>2</sup> -double	21 N/mm <sup>2</sup> -double	32 N/mm <sup>2</sup> -double
Toughened glass	50 N/mm <sup>2</sup> -single	53 N/mm <sup>2</sup> -single	56 N/mm <sup>2</sup> -single
	43 N/mm <sup>2</sup> -double	46 N/mm <sup>2</sup> -double	48 N/mm <sup>2</sup> -double

## 1.2 *Vibration*

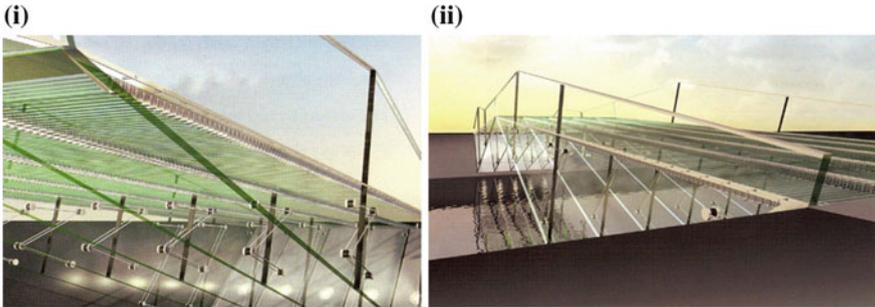
Over the past years there are several cases of footbridges experiencing severe vibration due to pedestrian loading. On the opening day in June 2000 the Millennium Footbridge, London experienced horizontal vibration induced by horizontal synchronized pedestrian load which was caused by 8000–10,000 people crossing the bridge. As a result, dampers were fitted to the Millennium Footbridge to lessen the “sway” caused by high pedestrian densities. Generally, structures like pedestrian footbridges are subject to static and also dynamic loading. If magnitude of the vibration coincides with natural frequency of the footbridge, resonance occurs and the structure can become unsafe [2]. Hence, footbridges must be designed so as not to be susceptible to vibrations. For the analysis of structural vibrations is necessary to calculate the natural frequencies of the structure and then determine the response to the expected excitation. In this way it can be determined whether a particular structure will fulfill its intended function. Conventional beam footbridges of spans greater than 25 m are likely to have a fundamental natural frequency within the range of the input excitation caused by pedestrians crossing the structure. A valuable closed-form approximation is given in BS5400 Part 2, [3]. According to Hauksson [4], many footbridges have vertical and horizontal frequency of 1.4–2.4 Hz and 0.7–1.2 Hz respectively. When walking over a bridge pedestrians are more tolerant of vertical vibration than horizontal vibration. Based on BD37/01, [5] the total minimum range of allowable vertical and horizontal frequencies are 5 and 1.5 Hz respectively. Therefore, bridges are susceptible to suffer excessive vibration under pedestrian action if the frequency is below the minimum range mentioned. It is also essential to consider both the horizontal and vertical excitation arising from pedestrians using the structure.

## 2 **Model Analysis of Glass Footbridge**

Figure 1 shows a detailed model of a glass footbridge that has not been constructed yet. This model was taken from a book titled *Glass in Structures* (Nijssen 2002). The concept was by Joris Luchinger, a graduating student, who drew and sent the drawing as shown in Fig. 2 for his project submission in a design competition. The goal of the competition was to propose a structure that can be used to cross the wide waters in the Florida area in The Netherlands. Joris Luchinger proposed a complicated footbridge, entirely made of glass. The footbridge has six large glass beams used as its primary girders. The beams are tapered in the middle of the span to create their “just not meeting” appearance. Each glass beam comprises of three longitudinal panels, and each panel is formed from four layers of 15 mm thick toughened glass, laminated by resin. Meanwhile, for each secondary beam which spans between the primary beams, their height is 150 mm and consists of  $2 \times 10$  mm annealed laminated glass rectangular plates. These secondary beams



**Fig. 1** Architectural drawing of a glass footbridge (Nijse 2002)



**Fig. 2** **i** Closeup view of glass footbridge. **ii** Side view of glass footbridge (Nijse 2002)

are at 30 mm center to center making a total of 300 beams forming the floor of the bridge. The primary beams which are also known as the main girders are connected to the secondary beams by a stainless steel shoe fastened in an inverted U-profile. The small secondary beams are ensured of lateral stability by providing tensioned steel cables in the plan of the bridge deck.

### 3 Modeling Approach

The use of glass as a structural material has undergone a marked change in the world of structural engineering. To create safe structures, it is necessary and common in any engineering design to analyse the structure before it is constructed. It is also wise to think ahead during early stage of conceptual design, making approximate calculation in the process, so that problems that may occur in the structure can be minimized. Therefore, it is good practice to develop a realistic Finite Element (FE) model for structural simulations before construction.

For this study the analysis, using a general purpose structural analysis programme, i.e., SAP 2000 has been performed. This programme is suitable for the analysis of structures subject to static and dynamic loadings. In this investigation, the structural response of the model in terms of its displacement and resulting forces due to the excitation of loads was determined.

In using SAP 2000, values of the material and section properties, support and loading conditions and dimensions of the model become the input data for the programme in order to determine the behavior of the model. Using this numerical model different types of support conditions were investigated. Thus, the maximum and minimum bending moment, shear force and deflection were obtained. Also the frequency and deflection limits of the glass footbridge were determined in order to satisfy the design code limits for footbridges as specified in BD 37/01, [5].

For the combination values, the dead load  $G_k$  and imposed load  $Q_k$ , a partial factor of safety of  $\gamma_f = 1.0$  was applied to all load combinations at serviceability limit state. The glass footbridge finite element model carries a uniformly distributed dead load from deck slab of 1.47 and 0.74 kN/m and a uniformly distributed imposed load of 5 and 2.5 kN/m for the inner and edge girders respectively.

### 3.1 Formation of the 2D Model

To carry out the analysis, a 2D model of an inner girder was created using SAP 2000. In order to create a simple 2D model, the structural plan in a 3D view is first considered, before a typical 2D structure can be isolated. As stated earlier, the original bridge of the structure consists of six large panels arranged to be 1.0 m apart from each other. There are 300 small secondary beams placed perpendicular to the panels, where each beam is 1.0 m in length and 60 mm in depth, forming the floor of the bridge. However, for this investigation, the length and depth of the secondary beams was converted into an equivalent width and depth of a flat slab, 1.0 m and 60 mm respectively. The six large glass panels were modeled using beam finite elements. The above consideration simplified the input data for SAP 2000.

The beam was modeled to include a hinge at the middle of the span. This non-prismatic girder was divided into seven elements. As shown in the finite element model in Fig. 3, the seven elements labeled as FSEC1, FSEC2, FSEC3, FSEC4, FSEC5, FSEC6, and FSEC7, define the finite beam elements of the main girder under investigation.

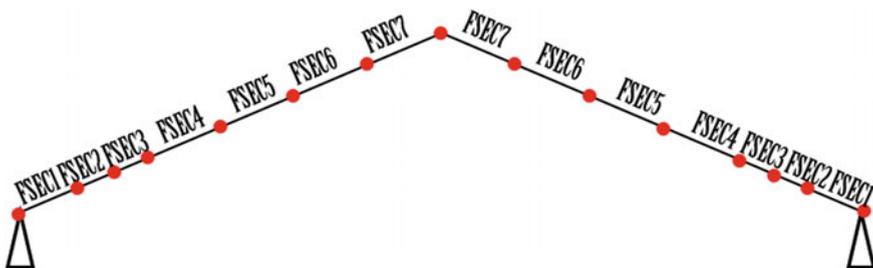


Fig. 3 Finite element model of girder (2D view)

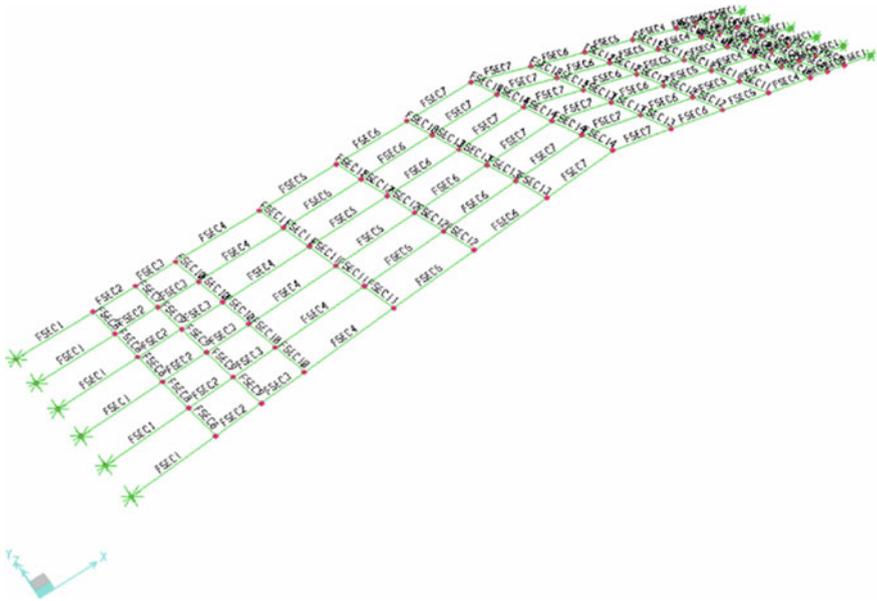
Every beam element has a constant width, 60 mm, but with different heights and lengths thus creating different values of longitudinal sectional area, volume, and mass. The other important input data necessary for a finite element model is the material properties of its elements. Therefore, all beam elements were given a Modulus of Elasticity, density and Poisson's ratio as  $70 \text{ kN/m}^3$ ,  $2500 \text{ kg/m}^3$  as 0.22 respectively. These values have been taken from a book titled Structural use of glass in buildings (Institute of Structural Engineering), and are typical for annealed glass.

### ***3.2 Formation of the 3D Model***

For the formation of this 3D model, the structure is modeled into six large glass panels joined together with a deck slab, 60 mm thick. Hence, the main beam (or girder) defined in the 2D modal analysis is duplicated into five other girders which are at 1 m center to center, making a total of six girders all together. However, for the 3D model analysis, the uniformly distributed dead and imposed loads from deck slab, which are transferred to the outer or edge girder, differs from the inner girder by a half, since the edge girder only carries half of the deck slab width. In the 2D model analysis, only beam finite elements of the primary girder are taken into consideration. In contrast, in the 3D model analysis, both primary and secondary beam finite elements are defined in the Programme SAP. Each secondary beam is modeled as seven beam elements to simulate the solid deck of 60 mm thick. As shown in the finite element model in Fig. 4, the seven beam finite elements labeled as FSEC8, FSEC9, FSEC10, FSEC11, FSEC12, FSEC13, and FSEC14, define the finite elements of the secondary beams under investigation. All components in the 3D model, i.e., primary and secondary beams exhibit the same material properties of glass as specified in Sect. 3.1. For this specific analysis, every secondary beam had a constant height and length of 60 and 1000 mm respectively. However, their widths are different, thus creating different values of section properties.

## **4 Comparison Between the 2D and 3D Numerical Models**

The aim of carrying out the 2D and 3D finite element analysis was to investigate the response of the glass bridge structure due to static loads. The behavior using different types of support conditions, i.e., pinned-pinned (ModelPP) or fixed-fixed (ModelFF) supports were also investigated. Hence, FEA using both types of supports were conducted and the results are compared. The analysed models produced values and locations of maximum bending moment, shear force and deflection. Tables 2, 3 and 4 compare the maximum moment, shear force, and deflections obtained from the 2D and 3D models. In the 2D analysis all the moments are carried by the primary beams, hence the moments are slightly higher than in the 3D



**Fig. 4** Finite element model of glass footbridge (3D view)

**Table 2** Comparison of maximum moment between 2D and 3D model

Supports	Max moment 2D model		Max moment 3D model		Max moment, % difference between models
	Value kNm	Location	Value kNm	Location	
ModelPP	173.2 (+ve)	At quarter span	164.2 (+ve)	At quarter span	4.2
ModelFF	499.3 (-ve)	At support	449 (-ve)	At support	10.9

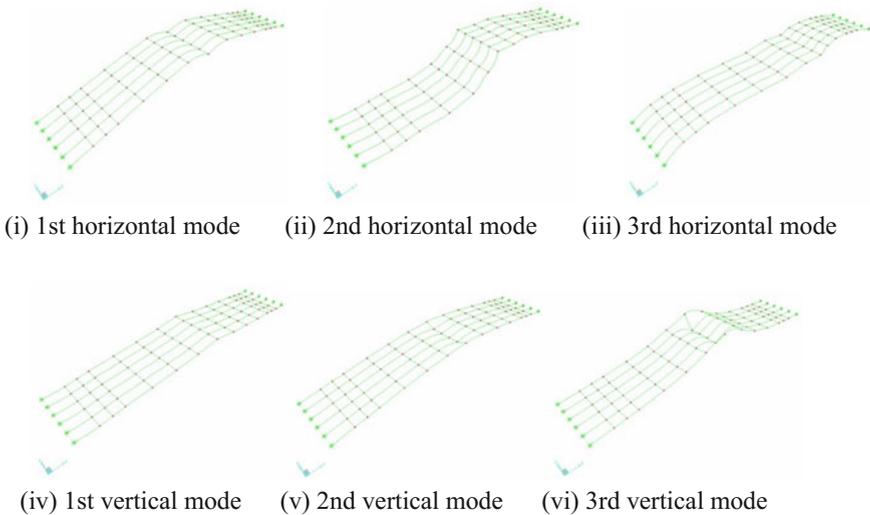
analysis because in 3D the secondary beams also help in carrying part of the moments. The 2D analysis is expected to give the maximum deflection due to the fact that the maximum moments were obtained from this model there by giving the maximum deflection. Whereas, the 3D had the maximum shear force because the secondary beams will also contribute part of the shear and total shear will be carried by the primary beam. While in the 2D model there will not be any contribution from the secondary beams.

**Table 3** Comparison of maximum shear force between 2D and 3D model

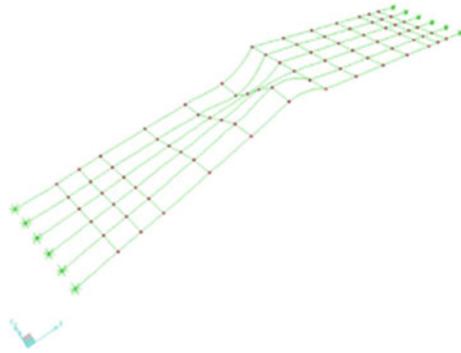
Supports	Max shear force 2D model		Max shear force 3D model		Max shear force, % difference between models
	Value kN	Location	Value kN	Location	
ModelPP	58.3 (-ve)	At support	64.4 (-ve)	At support	10.5
ModelFF	97.5 (-ve)	At support	98.4 (-ve)	At support	0.9

**Table 4** Comparison of maximum deflection between 2D and 3D model

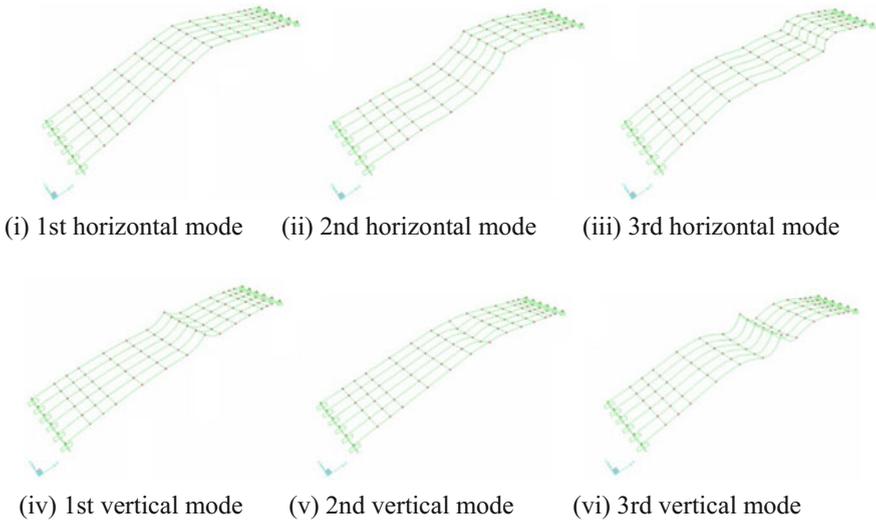
Supports	Max deflection 2D model		Max deflection 3D model		Max deflection, % difference between models
	Value mm	Location	Value mm	Location	
ModelPP	28.3	Near middle span	24.6	Near middle span	13.1
ModelFF	3.1	Near middle span	2.7	Near middle span	12.9



**Fig. 5** The first three horizontal and vertical modes of the model with pinned-pinned supports

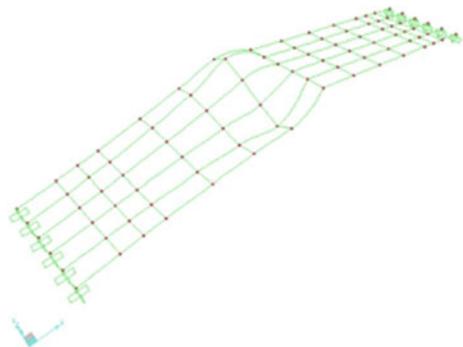


**Fig. 6** Torsional mode of the model with pinned-pinned supports



**Fig. 7** The first three horizontal and vertical modes and frequencies of the model with fixed-fixed supports

**Fig. 8** Torsional mode of the model with fixed-fixed supports



## 5 Frequencies and Modes of Vibration on the Models

Generally, a 3D modal analysis gives three types of mode shapes, i.e., horizontal, vertical and torsional as, compared to a 2D modal analysis which can produce only two types of mode shape, namely vertical and horizontal. Figures 5 and 7 show the first three horizontal and vertical modes and frequencies of the 3D model with pinned-pinned and fixed-fixed supports respectively. Figures 6 and 8 show the torsional mode and frequencies of the model with pinned-pinned and fixed-fixed supports respectively.

BS5400 states that if the fundamental frequency of vertical and horizontal vibration is less than 5 and 1.5 Hz respectively, the risk of upwards and lateral movements of unacceptable magnitude may occur and should be considered in the design. However, for this specific analysis of the glass footbridge the results obtained clearly shows that frequencies obtained for both conditions are within the required limits. A comparison of the vertical vibration criteria using pinned-pinned and fixed-fixed support conditions is presented in Tables 5 and 6 respectively. A comparison of the vertical vibration criteria indicates that the frequency obtained from the 3D model is only slightly higher than the values obtained from the 2D model by factors not exceeding more than 5.4%. This also indicates that there is a good agreement between the 2D and 3D model with a maximum difference in the order of 5%.

**Table 5** Comparison of the frequency and mass participation factor between the 2D and 3D models for the pinned-pinned supports

No. of mode	2D model		3D model		Maximum frequency, % difference between models
	Calculated frequency [Hz]	Mass participation factor (%)	Calculated frequency [Hz]	Mass participation factor (%)	
1st vertical mode	5.68	76.8	5.9	76.7	3.9
2nd vertical mode	31.2	77.4	32.4	77.3	3.8
3rd vertical mode	41.6	87.9	42.7	84.7	2.6

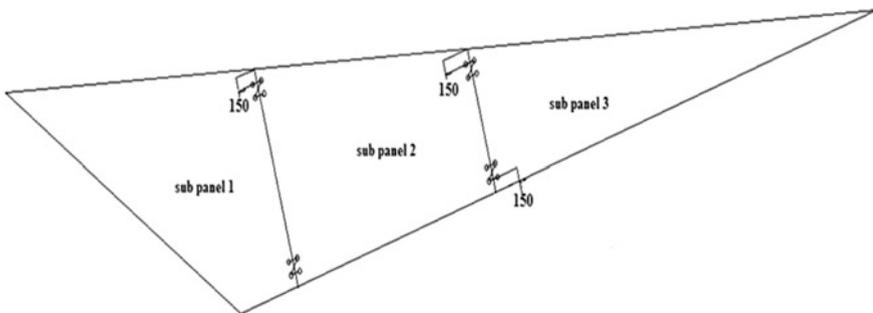
**Table 6** Comparison of the frequency and mass participation factor between the 2D and 3D models for the fixed-fixed supports

No. of mode	2D model		3D model		Maximum frequency, % difference between models
	Calculated frequency [Hz]	Mass participation factor (%)	Calculated frequency [Hz]	Mass participation factor (%)	
1st vertical mode	18.6	50.7	19.6	50.3	5.4
2nd vertical mode	32.4	51.0	33.5	50.5	3.4
3rd vertical mode	58.5	70.6	60.9	70.1	4.1

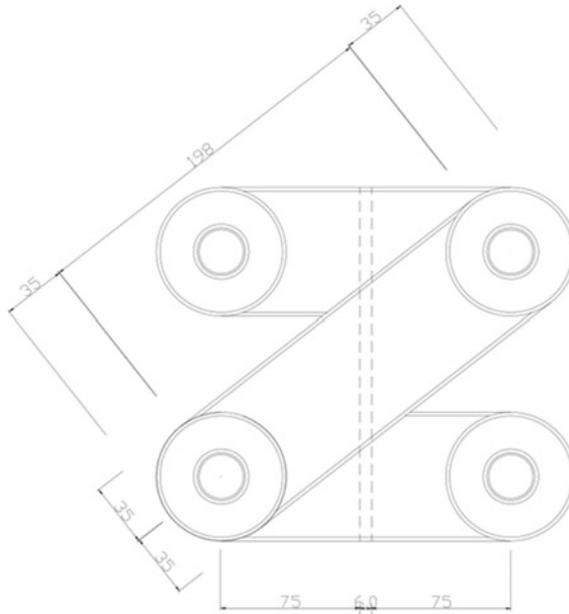
## 6 Connections

For steel connection design calculations, the average bearing stress, shear and tensile stress is required. However, for a brittle material like glass, the approach for its connection design procedure is comparatively more rigorous. Besides needing the value of the average bearing, shear and tensile stress, the design calculation also needs the value of the localized tensile stress concentration to ensure a safe design. In the process, forces developed should be properly and smoothly transferred between the glass members through the steel plates and bolts of the connections.

Due to the large size of each glass panel, being almost 10.5 m in length with a variable depth up to 2.8614 m, each panel needs to be subdivided into at least three smaller size panels which are connected with each other at Node 3 and Node 5 as shown in Fig. 9. Each sub-panel is formed from four layers of 15 mm thick toughened glass. Figure 10 shows the detail connection where the sub-panels are fixed together. At the connection, two connectors are used to transfer the bending



**Fig. 9** Sub panel with connections



**Fig. 10** Connection details Adopted from Nijssse (2002) (All dimensions are in mm)

**Table 7** Stresses at connection

Type of support	Maximum moment, $M$ (kNm)	Vertical distance, $d$ (mm)	$F_{\text{tension}} = M/d$ (kN)	Tensile area $A$ (mm <sup>2</sup> )	Stress in one strap = $(F_{\text{tension}}/A)/2$ (N/mm <sup>2</sup> )
Model PP	238.2	1325.4	179.7	480	187.0
Model FF	691.8	2770.7	249.7	480	260.1

moment between the sub-panels. For the purpose of designing the connectors at Node 5, the maximum bending moment value along the panel is used as the design moment acting on the connection. Hence, for Model PP the maximum bending moment in the large panel at this location is 238.15 kNm as given in Table 7. Once the connectors have been selected, stress levels in the connection will be checked.

The following shows the procedure adopted for the design of the connection.

Step1: To determine the force and type of bolt at Node 5 for Model PP;

$$\begin{aligned}
 \text{Moment acting on the connection, } M &= 238.2 \text{ kNm} \\
 &= 238.2 \times 103 \text{ kNm}
 \end{aligned}$$

Vertical Distance,  $d = (\text{Height of beam at node 5}) - (2 \times \text{Height of the connector}) = 1625.4 - 2 \times 150 = 1325.4 \text{ mm}$

Note that the vertical distance  $d$ , is defined as the total height of the beam at node 5, minus the height of the two connectors. (Each connector is 150 mm high.)  
Horizontal shear force acting on the connection,

$$\begin{aligned} F_{\text{tension}} &= M/d \\ &= (238.2 \times 103 \text{ kNm}) \\ &= 1325.4 \text{ mm} \\ &= 179.7 \text{ kN} \end{aligned}$$

The above implies that the shear capacity of the connection bolts should be more than 179.6 kN for a safe design. Hence, consider a total of 8, M20 Grade 8.8 bolts in accordance with BS 4395: Parts 1 & 2 with an individual shear capacity of 184 kN in double shear.

Total shear capacity from two bolts is  $2 \times 184 = 368 \text{ kN}$  and as  $179.7 < 368 \text{ kN}$  the connection is OK!

Step2: To check the stress level;

Select steel plate 150 mm height, 70 mm wide and 10 mm thick.

Tensile area =  $(70 - (20 + 2)) \text{ mm} \times 10 \text{ mm} = 480 \text{ mm}^2$

where diameter of bolt = 20 mm and

clearance hole = 22 mm

$$\begin{aligned} \text{Stress} &= (\text{tensile force}/\text{tensile area}) \\ &= (179.6 \times 103 \text{ N})/(480 \text{ mm}^2) \\ &= 374.2 \text{ N/mm}^2 \end{aligned}$$

However, as there are two straps carrying this load, one each side of the glass beam this strap force can be divided by two; hence the tensile stress in each strap is  $187 \text{ N/mm}^2$ . Since the steel grade S275 and the stress in one strap is less than  $275 \text{ N/mm}^2$ , therefore the selected strap is adequate. Therefore, two connectors with bolts size M20 Grade 8.8 are placed at Node 3 and Node 5 in Model PP. The above steps are repeated when designing the connection at Node 3 and Node 5 in Model FF, where the maximum moment 691.8 kNm for the panel is taken to be the moment acting at the connection.

## 7 Discussion, Conclusion, and Recommendations

This paper presents the investigation into the behavior of a glass footbridge as shown in Fig. 2. The footbridge is made of toughened glass, has six primary beams or panels and 3000 secondary beams which act as the floor deck. The 2D finite

element model shown in Fig. 3 is created using the Program SAP 2000, which is a finite element general purpose program. The model is formed using beam finite elements. The model having pinned-pinned supports, Model PP was analysed and the analysis was repeated with model having fixed-fixed support conditions, Model FF. Values in Table 4 indicate that the type of supports, influence the analytical results, where Model PP has comparatively higher maximum deflection whereas Model FF has higher maximum moment and shear force.

Maximum stresses for the models are calculated, where for Model PP and Model FF are 18.1 and 7.32 N/mm<sup>2</sup> respectively. Since these values are less than the tensile failure strength of toughened glass, typically 43–50 N/mm<sup>2</sup>, the footbridge using this type of toughened glass is considered to be safe. Tables 1, 2 and 3 compare the maximum moment, shear force and deflection obtained from the 2D and 3D models. In the 2D analysis all the moments are carried by the primary beams, hence the moments are slightly higher than in the 3D analysis because in the 3D model the secondary beams also helps in carrying part of the moments. The 2D analysis is expected to give the maximum deflection due to the fact that the maximum moments were obtained from this model there by giving the maximum deflection. Whereas, the 3D had the maximum shear force because the secondary beams will also contribute part of the shear and total shear will be carried by the primary beam. While in the 2D model there was no contribution from the secondary beams. The maximum deflection was 28.3 and 3.1 mm for model PP and Model FF respectively. Since these values are lower than the limiting value of 82.0 mm calculated based on code of practice, therefore the footbridge is safe.

Due to the large size of the glass panel (representing the primary beam), it was subdivided into smaller size panels which needed to be connected together. At the connections, connectors using steel bolts and steel straps were selected. The stress levels at the connections were checked and found to be adequate.

Although the analytical results using the 2D model was expected not to be very different from the 3D model, this investigation proves that this was in fact true, because the results differ only slightly as shown in Tables 2, 3 and 4. Modal analysis was carried out to determine the frequencies and mode shapes due to the vibrations of the footbridge. Modal analysis using the 2D model produces frequencies in a vertical mode only, whereas using the 3D model frequencies in three different modes can be obtained, vertical, horizontal, and torsional. Because the frequencies of vertical and horizontal vibrations of this footbridge are higher than the minimum value required as specified in the standard, therefore vibrations of an unacceptable magnitude would not occur in this footbridge. Because, the checks carried out indicate that the footbridge satisfies the design criteria, the footbridge design is considered to be safe and the structure is almost ready to be constructed.

Although a large portion of the glass bridge has been designed in this investigation there remains addition work which needs to be undertaken before the structure can be fabricated and erected. Further consideration has to be given to the connections, especially the support connections, which are subject to high shear loads and also to the bearing stresses in the glass adjacent to the bolts. Because the main beams are laminated careful consideration has to be given to the material

chosen to use between the individual laminations. It is important that the laminated beam acts as one complete unit and that stresses are uniformly distributed throughout the thickness of the beam otherwise the outer laminations may become overstressed and fail prematurely.

As the proposed glass footbridge is a novel structure, if finance is available it would be sensible to either construct a model of the structure or preferably to monitor the actual structure to check that the measured stresses under full load are in accordance with those calculated from the finite element analysis. In addition, the fundamental frequency of the structure could be obtained by dynamically exciting the structure and this could also be checked against the calculated value.

In the future it is expected that more glass structures with maximum transparency will be developed. Such structures free engineers from building masonry walls and steel frames and beams, which allow for more space and freedom.

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## References

1. Nijssen, R.: *Glass in Structures*, Birkhäuser, Berlin (2002)
2. Smith, J.W.: *Vibration of Structures: Applications in Civil Engineering Design*. Chapman and Hall, Bristol (1998)
3. Maguire, J.R., Wyatt, T.A.: *ICE Design and Practice: Dynamics: An Introduction for Civil and Structural Engineers*, 2nd edn. Thomas Telford Publishing, London (2002)
4. Hauksson, F.: *Dynamic behavior of footbridges subjected to pedestrians-induced vibrations*. Master Dissertation, Lund University (2005). Retrieved 17 Dec 2007, from Lund University Digital Library
5. BD37/88: *Departmental Standard—Loads for Highway Bridges*. Highway and Traffic Agency, London (1989)