Glass Struct. Eng. (2016) 1:451–460
DOI 10.1007/s40940-015-0002-1

CASE STUDY

Folded plate structures made of glass laminates: a proposal for the structural assessment

Stefan Marinitsch · Christian Schranz · Martien Teich

Abstract This paper presents a possible approach for the assessment of folded plate structures made of glass laminates using a new connection detail. Following a brief introduction and discussion of the experimental connection detail, the results of conducted testing are summarized. An extensive numerical investigation using ANSYS is performed. Findings from these numerical investigations of the connection detail, namely a proposed load interaction and the influence of the kink angle on the utilization will be touched on. A simplified modelling procedure for the assessment of a structural system is presented and its results are discussed for a selected configuration. It is shown that the new connection detail is feasible for folded plate structures spanning up to 15 m. The paper concludes with proposing further research and an outlook.

Keywords Glass · Folded-plate-structure · Linear connection · Bearing capacity · Stability

S. Marinitsch (✉) · C. Schranz · M. Teich
Vienna, Austria
e-mail: stefan.marinitsch@seele.com

C. Schranz
e-mail: Christian.schranz@tuwien.ac.at

M. Teich
e-mail: Martien.teich@seele.com

1 Introduction

1.1 Folded plate structures

Conventional building materials have been able to claim their own design language. Concrete is typically used to its advantage to produce planar elements or to adapt to free-form (cast) shapes or heavy volumes. For steel or timber the designers' thinking is typically driven by a linear language, originating in the nature of the semi-finished products of the beams and girders.

When Girkmann (1959) referred to the advantages of plane load-bearing structures, he was referring to concrete and steel. Excited by the efficiency of such structures, more recently research teams began to adapt them for a variety of alternative materials. Buri and Weinand (2010) constructed a folded arch formed of ply-wood, Spalding's (2013) structures are made of plastics, Blandini (2008) formed a curved glass dome, Wurm (2007) and Bagger (2010) presented faceted dome structures with glass.

For the flat material glass, folded-plate structures (e.g. in Fig. 1) seem an ideal candidate when in need for an appropriate design-language. Recent research conducted at the University of Minho (Carvalho et al. 2014) produced a temporary structure subjected to short term loading. Designers used a similar approach for the internal glass ceiling of the Zurich Stadtbad (Willaret and Meyer 2011).

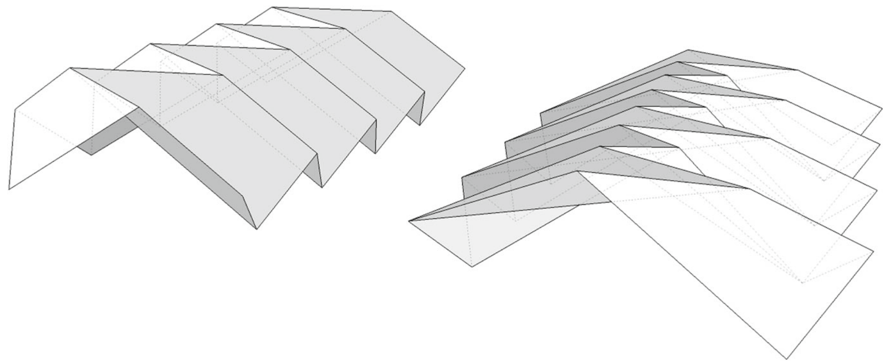

Fig. 1 Parallel and diagonal pattern with a reverse fold (Marinitsch et al. 2015b)

A key hurdle to master is not the load bearing capacity of the glass itself. Research conducted by Englhardt (2007) and Luible (2004) has proven the suitability of the material for substantial in-plane loading. The search for an appropriate connection detail that safely transfers loadings from one plate to the other (Wurm 2007), appreciating the material characteristics of the used components (Weller et al. 2010), is, however, more difficult.

1.2 Proposed connection detail

Following a detailed search for available, typically experimental, connection details, a draftsman's review of these details (Bagger 2010; Blandini 2008; Carvalho et al. 2014; Willaret and Meyer 2011; Wurm 2007) was carried out. The aim was to distil the positive design characteristics of the individual approaches and to combine as many of these characteristics as possible in a new (experimental) joint assembly for the use in a load bearing glass structure.

Primary design objectives were a maximized in-plane loading capacity and a minimal rotational stiffness to avoid undue moments at the connection. Furthermore, the detail is to be characterized by a good-natured failure behaviour. Yielding of the connection is preferred to spontaneous glass breakage. Ideally, the detail can avoid local stress concentrations as they occur in bolted assemblies and incorporate the actual connection detail into the safety feature of the laminate (i.e. the interlayer). For the design, a fast installation and the possibility for glass-replacement during service-life had to be considered as well as the weathering of the detail.

The proposed connection detail is shown in Fig. 2. The glass units are formed of triple-laminated glass, incorporating metallic inserts into the interlayer. Two adjacent units are provisionally connected using rivets. Tolerances are accommodated in oversized holes along the fixings axis. Following this initial positioning, the cavity formed by the protruding inserts is filled with an epoxy-grout. This transforms the load transfer mechanism from friction grip to a tight fit assembly. Compression forces are passed through the grout and the inserts, tension forces travel through the inserts (via shear in the interlayer) from one side to the other. Shear forces are transferred by a continuous serration of the alternating shear dowels formed by the fold-returns of the metallic inserts and the rivets in combination with the contained grout. Stress concentrations due to the mechanical fixings are handled in the metal components and not the brittle material glass. The weathering of the detail is located between the outer glass plies, hiding the joint assembly and providing a flush surface. When viewed from the glass side, the grout disappears in the shadow gap formed by the two inserts along the edge.

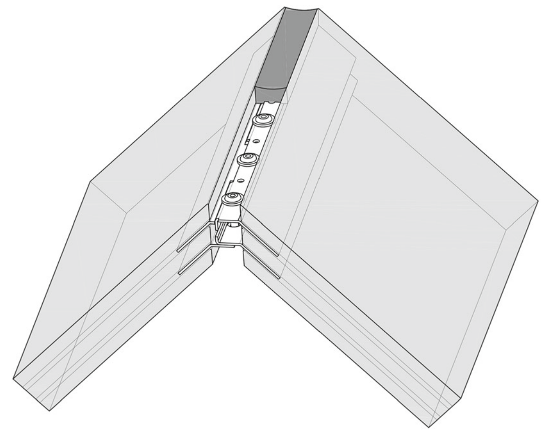

Fig. 2 Connection detail AA (Marinitsch et al. 2015b)

Table 1 Test series: quantity of conducted tests (*M* moment, *T* tension, *C* compression, *S* shear, *V* transverse load) (Marinitsch et al. 2015a)

Mode	M (20 °C)	M (60 °C)	T (20 °C)	T (60 °C)	C (20 °C)	C (60 °C)	S (20 °C)	S (60 °C)	V (20 °C)
L[a]	2	0	3	1	3	0	3	0	0
H[b]	3	6	3	3	3	4	3	4	6
Total	5	6	6	4	6	4	6	4	6

[a] Continuous displacement
[b] Displacement driven in hysteresis

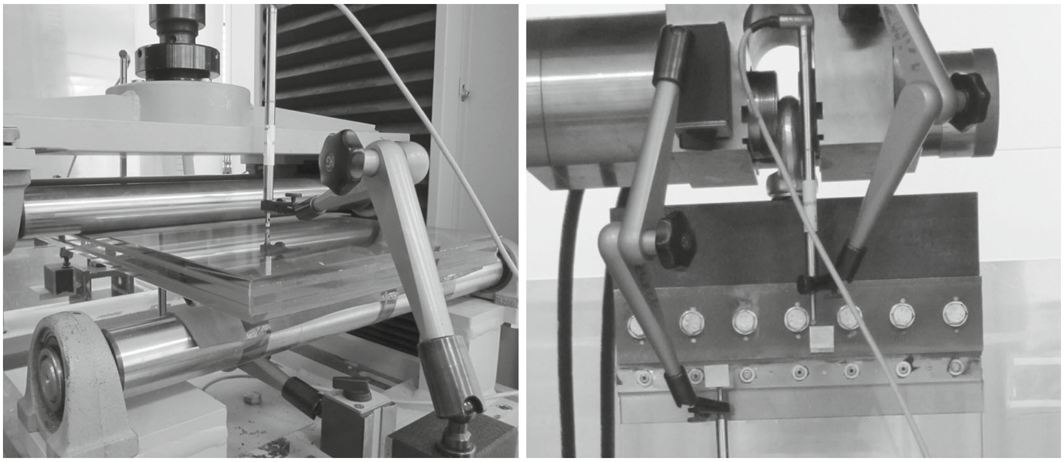

Fig. 3 Four-point-bending test (*left*) and tension test (*right*)

2 Testing

2.1 Overview

In order to verify the load bearing capacity of the developed connection detail, a series of tests are conducted (see Table 1). The test setup is described in Marinitsch et al. (2015a). Testing is carried out separate for the main loading modes to better understand the load transfer mechanisms, loading limits and the critical components. The specimen size is 350 × 350 mm for modes C, T, S and V (glass size) and 725 × 350 mm for mode M (assembly size). The inserts are formed of stainless steel (grade 1.4301), laminated with heat-strengthened glass using an ionoplast interlayer. The test series V are introduced to investigate the details capacity for transverse loadings as present in a kinked assembly. Tests are carried out for two temperature levels (ambient temperature 20 °C and increased service temperature 60 °C) for short term loadings only. The loads are applied displacement driven. The first set of samples is tested with a continuous displacement to determine a sensible hysteresis limit for the remaining specimens.

All tests are conducted on a ZwickRoell Z250 universal testing machine. In addition to the integrated displacement readings of the machine additional displacement transducers are positioned for all specimens (Fig. 3). These readings are used to validate the prediction accuracy for numerically derived deformations (Marinitsch et al. 2015a).

2.2 Test results

Table 2 summarizes the maximum test loads and the hysteresis limits for each mode. The connection is characterized by a high in-plane stiffness and a good rotational capacity when subjected to moment loading. All tests are stopped at the indicated maximum test loads. No glass breakage is observed when tested according to the planned setup. For all loading modes the failure is characterized by a deformation of the protruding metal inserts.

Table 2 Maximum test loads, hysteresis limit load, interaction load and displacement

Mode	Max. test load (kN) test stopped	Load (kN) hysteresis	Limit load (kN) interaction load	Displacement (mm) @ interaction load
M [a]	~4	1	2 (=570 Nm/m)	~4.20
T [a]	~40	5	5	~0.03
C [a]	~180	10	10	~0.01
S [bc]	~160	50	40	~0.18

Length of investigated connection: [a] 350mm, [b] 700mm, [c] in plane shear

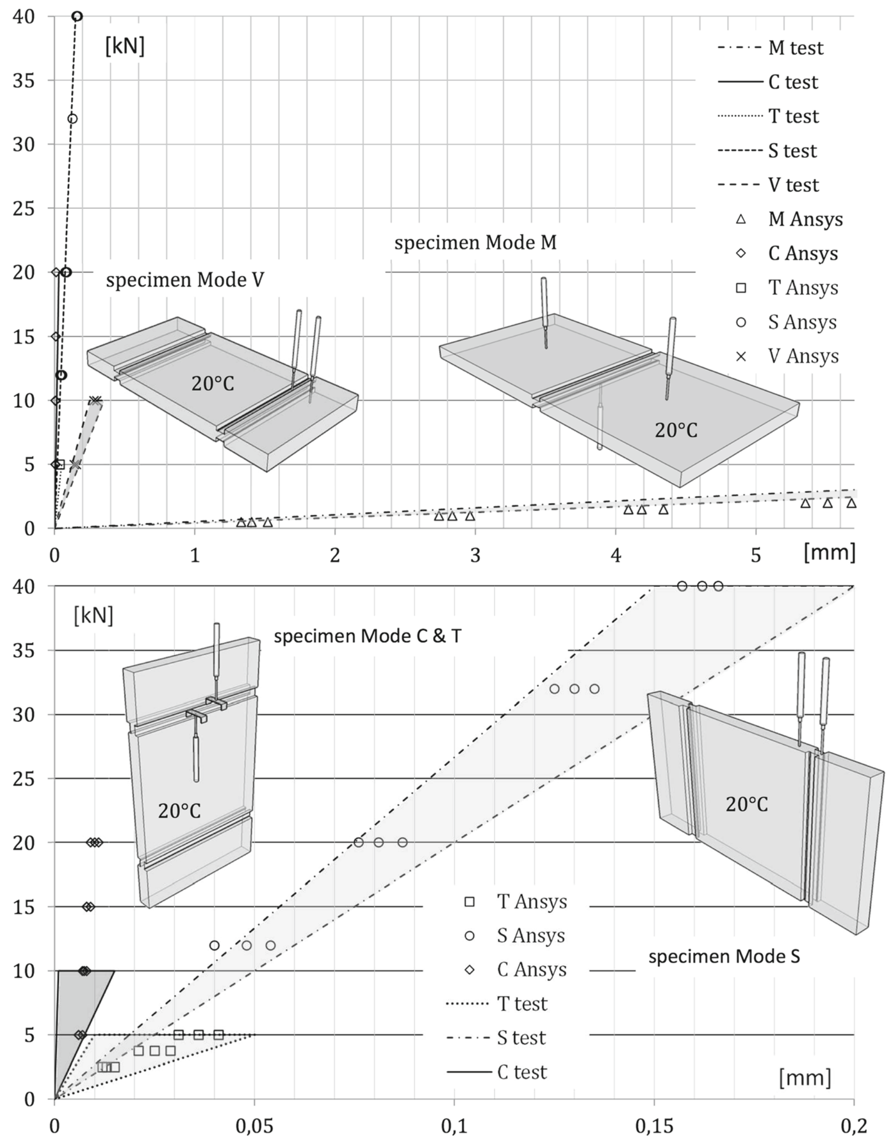

Fig. 4 Comparison of measured and computed data

The displacement readings in Table 2 are taken from the additional displacement transducers. The spread of the measured values is shown in Fig. 4. For mode M the value represents the reading of the gauge located at the underside of the specimen at the joint. For modes T, C and S the readings of the displacement transducers are used to calculate the local movement over the joint assembly. The data confirms a high in plane stiffness and a pinned (i.e. soft) behaviour for loadings inducing bending.

3 Numerical assessment of the connection detail

3.1 Modelling approach

The testing confirms the loading allowances for the main loading modes under short term loading. To assess a structural assembly a tool for load interaction is needed. In the present research a numerical approach is adopted. The geometrical non-linear behaviour of the connection detail (i.e. compression transfer only between glass edge and epoxy-grout) is modelled in the FEA-software ANSYS. All test specimens are modelled and loaded with the interaction load according to Table 2. The computed deflections are compared to the spread of the deflection readings of the displacement-transducers.

All models (M, T, C, S and V) use the same contact definitions and mesh settings. For the present quasi-static loads all components have been modelled using the higher-order 3D elements solid186 or solid187. Alternative modelling approaches for dynamic loading can be found in Kolling et al. (2012). The materials are modelled with linear-elastic properties (Table 3). This should be reviewed critically when temperatures around the glass transition temperature of the interlayer are assessed (see Hooper et al. 2012). In addition to the test loads the pre-stress of the rivets is accounted for in the models. The average pre-stress level is obtained by testing. The numerical ANSYS model for the test series M and T are shown in Fig. 5. A comparison of the computed deflections with the measured data confirms a useful match for all models (see Fig. 4). Details on the comparison can be found in Marinitsch et al. (2015a).

Table 3 Material properties

Description	Material	ρ (kg/m^3)	E (N/mm^2)	ν (−)	G (N/mm^2)
Steel, secondary components[a]		7850	200,000	0.30	76,923
Laminated inserts[c]	1.4301	7900	200,000	0.30	76,923
Epoxy-grout	HY70	1500	1757	0.23	714
Glass		2500	70,000	0.20	29,167
Ionoplast interlayer[b]	SentryGlas	950	567	0.453	195

[a] ANSYS material steel
[b] Values for 20 °C/1 min
[c] Incl. rivets

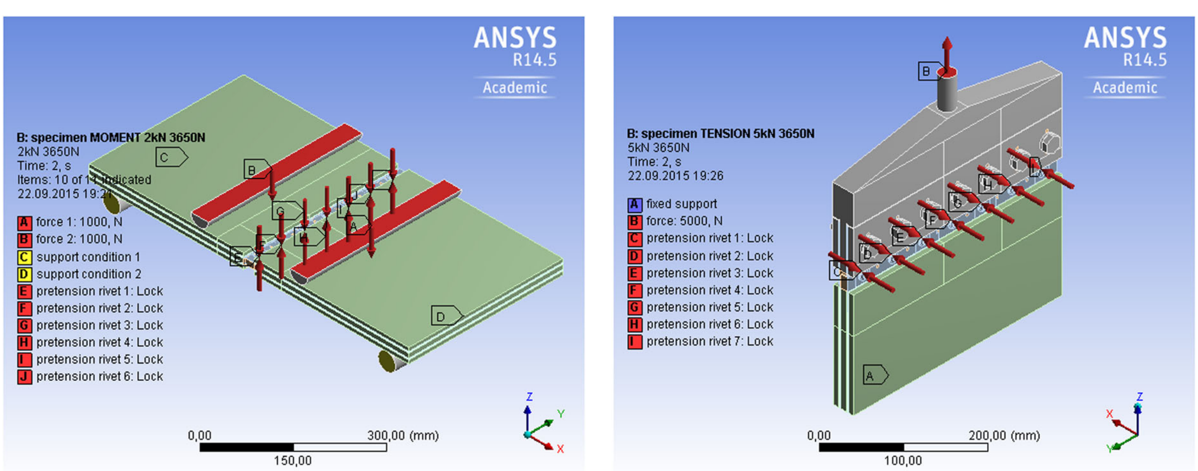

Fig. 5 Numerical model of the four-point-bending test (*left*) and the tension test (*right*)

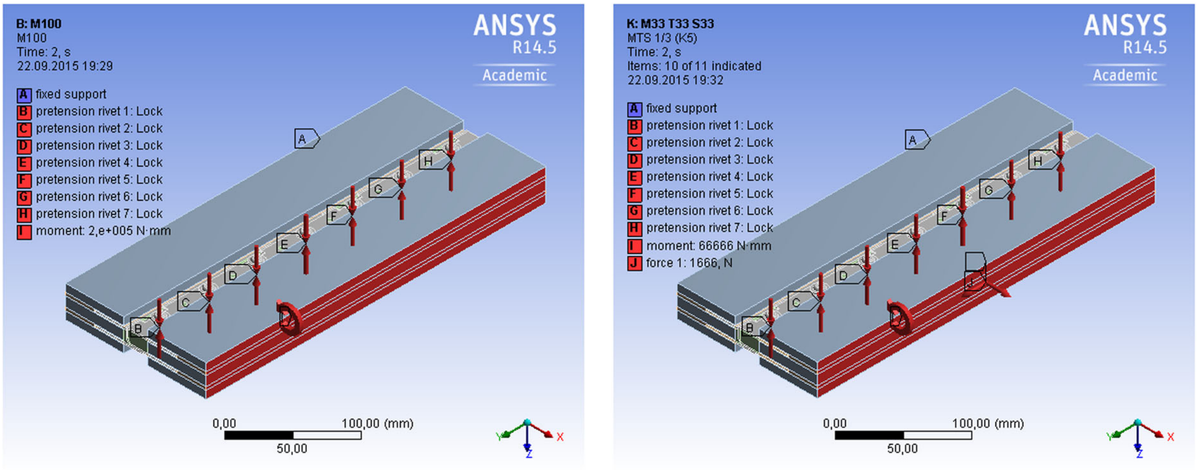

Fig. 6 ANSYS models for the load interaction analysis: mode M (*left*) and interaction M–T–S (*right*)

Table 4 Limit loads and load combination factors

Limit load/mode*					Load combination factors						
Mode	M	T	C	S	MT	MC	MS	TS	CS	MTS	MCS
M	1	–	–	–	0.5	0.5	0.5	–	–	0.33	0.33
T	–	1	–	–	0.5	–	–	0.5	–	0.33	–
C	–	–	1	–	–	0.5	–	–	0.5	–	0.33
S	–	–	–	1	–	–	0.5	0.5	0.5	0.33	0.33

* Reference load to calculate the reference stress for each mode = loading limit per mode

The numerical glass stresses show a good correlation to the test observations, where no glass breakage was observed. When the glass utilization for the limit load is multiplied with the factor present between maximum test load and interaction load, the resulting utilization remains below 1.

3.2 Load interaction

Based on the modelling principles used for the test specimens a new load interaction model is derived (Fig. 6). The model is loaded with forces according to Table 2 using the load combination factors listed in Table 4 (MC describes the load interaction between 50 % moment and 50 % compression loading, using the limit loads from Table 2). The interaction-model is loaded with the limit loads per mode (e.g. mode M, see Fig. 6 left). The stress levels in the inserts are compared with the values for the FEA-models of the test specimens (Fig. 5). In general there is a good correspondence between the results of the models. Small deviations due to the model change are considered uncritical.

The stresses under combined loading are reviewed with the figures found for the limit loads per mode on the interaction model (e.g. M–T–S with mode M, see Fig. 6 right, as well as mode T and S). Interactions of mode C and T with mode S exceed the reference limits set by the limit loads in localized areas. As the maximum test loads are significantly higher than the selected limit loads for interaction the observed peaks are considered uncritical. The proposed interaction scheme is deemed acceptable for the purpose of this research (Marinitsch et al. 2015b).

3.3 Influence kink angle

For the assessment of a folded plate structure the influence of the kink angle on the detail needs to be understood. A parametric model is set up using Autodesk Inventor. Once the first model is configured in ANSYS,

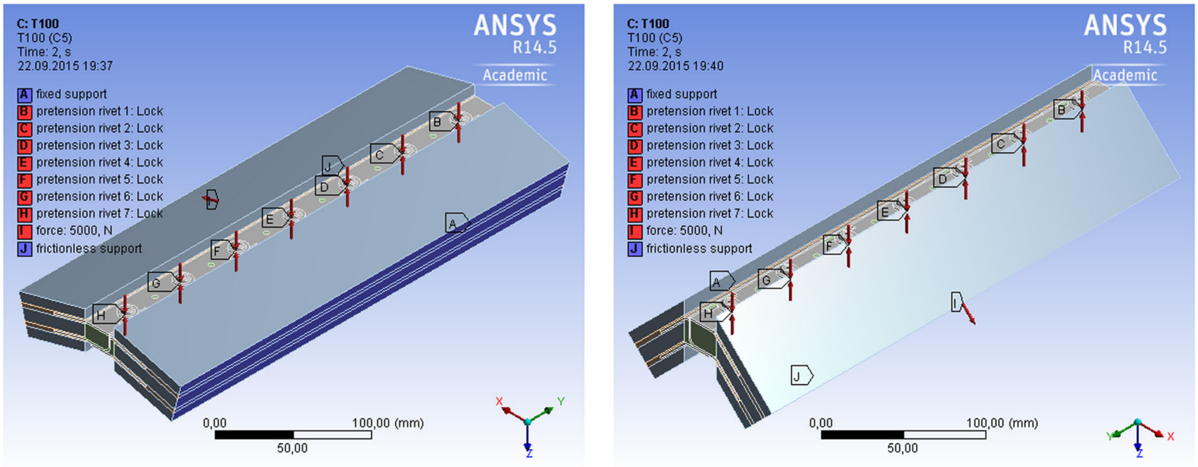

Fig. 7 ANSYS models with different kink angles for mode T: 150 ° (*left*) and 90 ° (*right*)

varying geometries can be investigated by changing the angle in the CAD-model without the need to set up the numerical model multiple times (Fig. 7).

The models are calculated with the limit loads for interaction only. Reducing the kink angle reduces the utilization due to a given moment loading. For in-plane loadings (T, C, S) the utilization increases. The observed increases are marginal and deemed uncritical. For the purpose of this research, the influence of the kink angle is considered negligible when compared with the 180° interaction model (Marinitsch et al. 2015b).

4 Assessment of a structural system

4.1 Modelling approach

Whilst the connection assembly was reviewed using a geometrical non-linear modelling approach, the assessment of a complete structural system is carried out with a simplified model (Fig. 8) in the FEM software Dlubal RFEM4. The connection behaviour is accounted for by defining a linear connection stiffness. To ensure the displacement behaviour of the selected approach is correct, it is checked for each loading mode on simplified models resembling the test specimens. The stiffness values are calculated using the interaction loads and displacements in Table 2. The stiffness applied in the structural model are listed in Table 5. The plates are supported at the furrows over a length of 300 mm. In addition, the structure is vertically supported along the perimeter, forming diaphragms at the short ends.

The laminated glass is modelled for the composite limits *no shear transfer* (OV) and *full shear transfer* (VV). For this study the spans 7.5 and 15 m and plate widths 1, 2 and 3 m are investigated. In addition to the self-weight of the structure, perpendicular surface-loads are applied in 0.5 kN/m^2 steps to a maximum of 2.0 kN/m^2. The connection forces along the ridge and furrow are used to assess the utilization of the connection and to compare it to the bifurcation-factor of the first eigenmode. The glass stresses are reviewed as a further design parameter.

The connection forces are compared to the limit values in Table 6 using Eq. (1). These equations follow the principle set out in Table 4 and are a first tool for a structural feasibility check.

$$\begin{aligned} M/M_{y,\mathrm{limit}} + T/T_{x,\mathrm{limit}} + D/D_{y,\mathrm{limit}} \leq 1 \\ M/M_{y,\mathrm{limit}} + T/T_{x,\mathrm{limit}} + Z/Z_{y,\mathrm{limit}} \leq 1 \end{aligned} \tag{1}$$

4.2 Discussion of results

In Fig. 9 typical first eigenmodes for the assessed assembly are shown. The singular mode is typically attributed to the end plates. When the first eigenmode is found singular, higher eigenmodes are multiple modes.

Figure 10 summarizes the results for a selected numerical assessment. The figure is split in four sections. The first row covers a span of 15 m, to the left for the composite state *no shear transfer* (OV) and to the

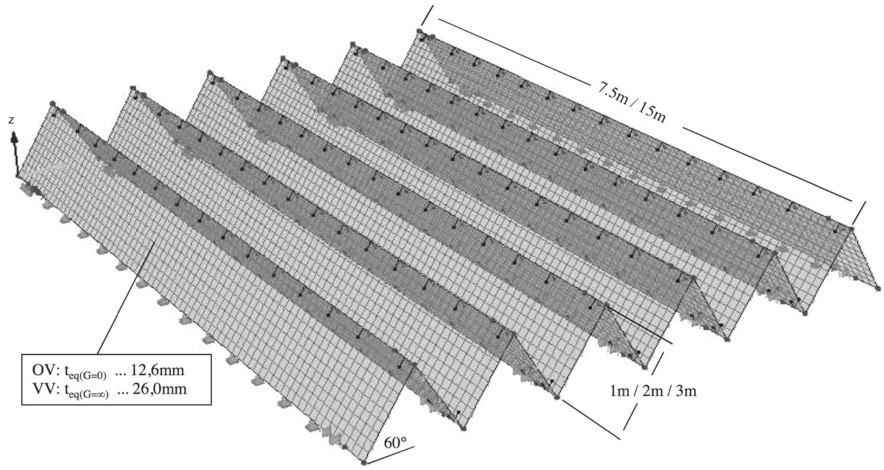

Fig. 8 Structural model using Dlubal RFEM4

Table 5 Connection stiffness used in the FEM simulation

	k_T (kN/m^2)	k_C (kN/m^2)	k_S (kN/m^2)	k_V (kN/m^2)	k_φ (kN/RAD/m)
RFEM	480,000	3,600,000	330,000	48,000	35

Table 6 Limit loads for interaction for 1m join length

$M_{y,limit}$ (kNm/m)	$S_{x,limit}$ (kN/m)	$T_{y,limit}$ (kN/m)	$C_{y,limit}$ (kN/m)
0.57	57.14	14.29	28.57

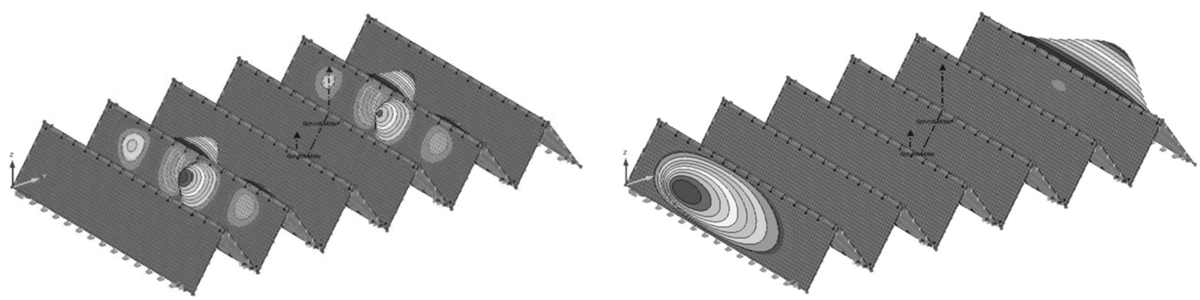

Fig. 9 Buckling modes: multiple (*left*) and singular (*right*) eigenmodes

right for the limit *full shear transfer* (VV), the second row a span of 7.5 m. In all graphs the vertical numbering to the left provides the bifurcation factor for the first eigenmode.

The scale to the right is assigned to the utilization. Both, the utilization of the connection detail according to formula (1), as well as the glass utilization are referred to in this scale.

The utilization of the connection detail and the glass are assessed for locations of maximum shear transfer and maximum moment for three different plate widths (1, 2 and 3 m). To account for the software's implementation of the linear connection stiffness, all in-plane forces for interaction are selected two mesh-points away from the connection. For the obtained shear forces this is a conservative approach. For each width the utilization of the governing location is shown in the graphs. 300 mm on either end of the structure are deemed part of the diaphragm detailing and are therefore not accounted for in the assessment. Figure 10 identifies the joint as the failure critical component. For all graphs the joint utilization reaches 100 % ($\mu = 1$)

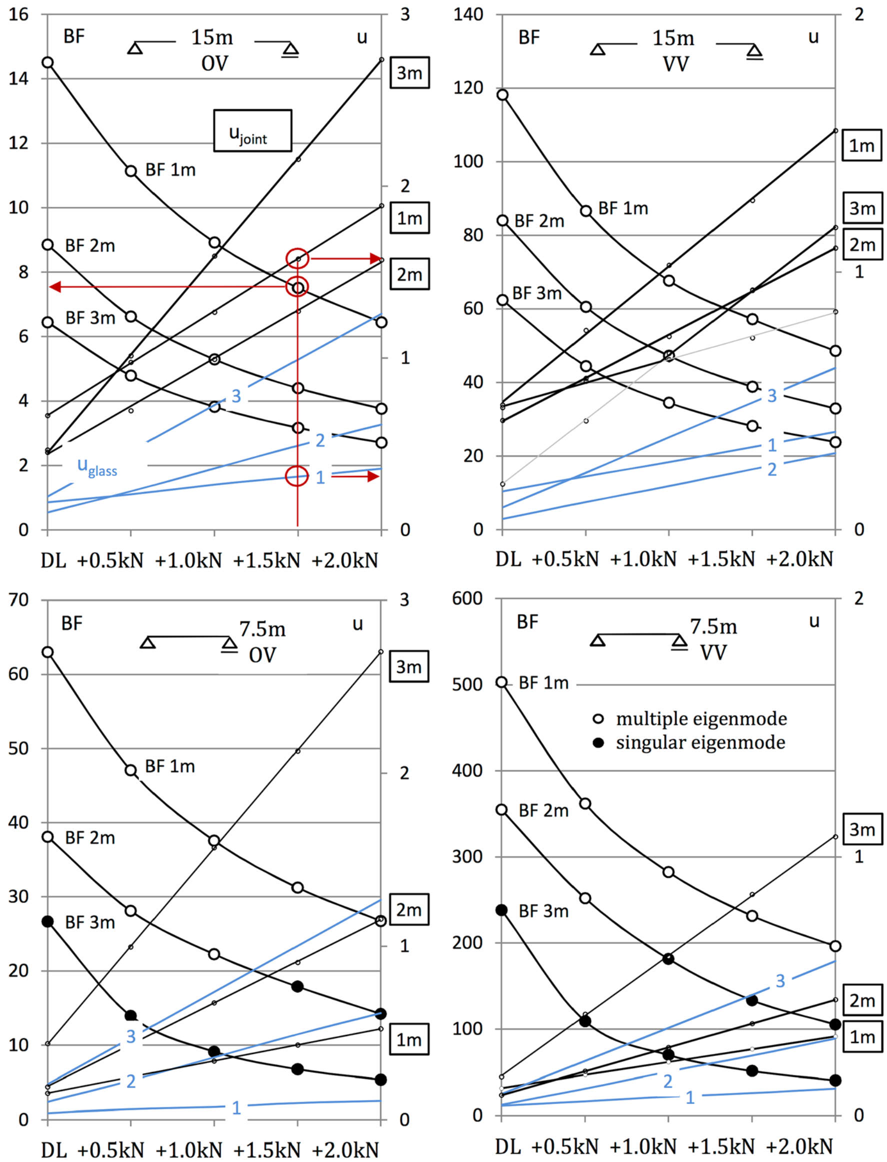

Fig. 10 Comparison joint and glass utilization with the bifurcation factor for a 60° fold and varying systems assessed according to Sect. 4.1

before the load bi-furcation factor becomes smaller than 1.

The same applies to the glass utilization when compared to the joints. The utilization of the glass (first principle stress compared to an allowable stress of 29 MPa for heat strengthened glass) is generally lower than the utilization of the connection detail. The maximum stress in the glass is typically located towards the connection for smaller plate widths and towards the plate middle for increased plate widths when moment loadings become dominant.

Reducing the span of the structure decreases the shear forces and the longitudinal plate forces parallel to the connection. Moment loading is unaffected by the span as the plate is supported between ridge and furrow. Increasing the plate width reduces the shear forces but increases the moment loading for the plate. Due to the rotational stiffness of the joint assembly, moments are introduced along the connection. The composite limits affect the stiffness of the plate due to the change of the effective thickness. When stability (plate-buckling) is reviewed smaller spans lead to bigger bifurcation-factors for equal loadings. The limit *no shear-transfer* is more critical with regard to buckling than the stiffer *full composite*.

In the following, Fig. 10 is explained using an example: When a vertical line is drawn at the load level of interest (e.g. DL+1.5 kN), it intersects with the glass utilization, the joint utilization as well as the bifurcation factor. For all results, the same plate width (e.g. 1 m) must be selected. The results for the utilization can be read on the right hand scale and the associated bifurcation factor on the opposite side. The marked sample in the graph indicates that at dead-load and 1.5 kN load the joint is failing ($\mu > 1$) whilst the glass is not critical ($\mu < 1$). No plate buckling is to be expected since BF > 1.

5 Conclusion and outlook

The numerical investigation indicates that the application of the proposed connection detail seems feasible for structures spanning up to 15 m. The connection detail is confirmed as the failure critical component in the assembly as strived for in the design objectives. This good-natured failure behaviour needs due consideration when the risk of progressive collapse is assessed.

The approach presented in this paper is not a ready-to-use design concept. The presented results are understood as a feasibility study outlining the possibilities folded plate assemblies offer for structural glass applications. The conducted testing and numerical assessment only discuss short-term loadings. Further research is needed to investigate the assemblies' behaviour under permanent or cyclic loading. The numerical interaction model as well as the assessment on the influence of the kink angle require further validation by testing. The interaction model should be refined to incorporate the currently not considered out of plane shear.

The sensitivity of the structural assembly on the connection stiffness and the associated temperature dependence should be investigated as well as the behaviour and durability of the interlayer-material for the intended application.

Acknowledgments The authors thank the industry for their support. Unterfurtner for providing the inserts, Saint Gobain for the glass, Kuraray for the Interlayer, Hilti for the epoxy-grout and sedak for their support in manufacturing and testing of the specimens.

References

Bagger, A.: Plate shell structures of glass, studies leading to guidelines for structural design. Lambert Academic Publishing, Saarbrücken (2010)

Blandini, L.: Structural use of adhesives in glass shells. In: Bos, Louter, Veer, (eds.) Challenging glass. Conference on architectural and structural applications of glass, pp. 185–191. IOS Press, Amsterdam (2008)

Buri, H., Weinand, Y.: Origami aus Brettsperrholz. DETAIL Zeitschrift für Architektur + Baudetail **10**, 1066–1068 (2010)

Carvalho, P.L., Cruz, P.J.S., Veer, F.A.: Connecting through the reinforcement: design, testing and construction of a folded reinforced glass structure. J. Facade Des. Eng. **2**(1–2), 109–122 (2014)

Englhardt, O.: Flächentragwerke aus Glas—Tragverhalten und Stabilität. Ph.D. thesis, University of Natural Resources and Life Sciences, Vienna (2007)

Girkmann, K.: Flächentragwerke. Springer, Wien (1959)

Hooper, P.A., Blackman, B.R.K., Dear, J.P.: The mechanical behaviour of poly(vinyl butyral) at different strain magnitudes and strain rates. J. Mater. Sci. **47**, 3564–3576 (2012)

Kolling, S., Schneider, J., Gebbeken, N., Larcher, M., Alter, C., Kuntsche, J.: Deformations- und Bruchverhalten von Verbundsicherheitsglas unter dynamischer Beanspruchung. Stahlbau **81**(3), 219–225 (2012)

Luible, A.: Stabilität von Tragelementen aus Glas. Ph.D. thesis, EPFL, Lausanne (2004)

Marinitsch, S., Schranz, Ch., Kolbitsch, A.: Untersuchungen zur Tragfähigkeit eines Verbindungsdetails für Faltwerke aus Glas. Bauingenieur **90**(6), 265–271 (2015)

Marinitsch, S., Schranz, Ch., Teich, M.: Faltwerke aus Glas. In: Weller, B., Tasch, S. (eds.) Glasbau 2015, pp. 201–211. Ernst & Sohn GmbH & Co. KG, Berlin (2015)

Spalding, V.: Die Kunst der Falte: Faltwerke aus plattenförmigen Kunststoff-Halbzeugen. Ph.D. thesis, Staatliche Akademie der Bildenden Künste, Stuttgart (2013)

Weller, B., Döbbel, F., Nicklisch, F., Prautzsch, V., Rücker, S.: Geklebte Ganzglaskonstruktion für das Leibniz-Institut für Festkörper- und Werkstoffforschung in Dresden. Stahlbau **79**, 34–40 (2010). doi:10.1002/stab.201001300

Willaret, P., Meyer, D.: A new folding glass roof for the historic city swimming hall Zürich. In: Proceedings of Glass Performance Days. pp. 622–624, Tampere (2011)

Wurm, J.: Glas als Tragwerk, Entwurf und Konstruktion selbsttragender Hüllen. Birkhäuser, Basel (2007)