Innovative steel-glass components for high-performance building skins: testing of full-scale prototypes

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Abstract High-innovation of products is a world-wide key-competitive factor. The most important technological achievements in modern architecture are attained by constructing smart building skins, usually by combining glass and metal. The European Research Fund for Coal and Steel (RFCS) project “S+G” (Steel+Glass) studies steel-glass composite systems for high-performance skins using adhesive junctions meeting requirements of as well energetic, technical and aesthetical disciplines. Within the research project cold-formed glass elements with a hyperbolic paraboloid shape were developed, where glass is structurally bonded with a metal frame. One of the focuses of the project was on full-scale tests on three different kind of prototypes, which have been performed to study the steel-glass composite system with various adhesives under different loading. Indication of several applicable adhesives for the steel-glass junction were provided. Among the products available on the market, three different-in-type materials were considered: High performance structural silicone, polyurethane-based adhesive and an innovative silicone structural adhesive. The strength and stiffness of single cold-formed cells under out-of-plane loading with regard to loads acting perpendicular to the surface were assessed, especially regarding the action on bent glass, the long-term behaviour

and the residual resistance after breaking of one or all glass panes of a laminated glass. The capability of glass to prevent buckling of slender steel members was a crucial issue to consider. This paper presents the main experimental results of full-scale tests regarding out-of-plane loading and first results of numerical investigations. The results demonstrate the possibility of using the structural bonded steel-bent glass composite structures as a facade element in modern architectural design.

Keywords Steel-glass composite · Adhesive · Hyperbolic-paraboloid surface · Component tests

1 Introduction

1.1 Aim of the European research project “S+G”

The starting position for the project was that, in modern architecture, metal (i.e. different kinds of steel or aluminium) and glass usually form the external envelope of a building, often called the “third skin”. This delimits the indoor living space, controls the energy transfer between inside and outside by selective filtering of heat and light, and defines the aesthetic appeal of the building. As the demand for complex geometries and improved performance increases, innovative and not uniform building envelope solutions have to be devised. Here the interaction of the single components in a facade element is an important issue to be considered.

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The research on the single components towards aesthetic and technical requirements is carried out in many different projects. Within several research projects and publications characteristics and material behaviour of for example laminated cold bent glass and adhesives has been investigated. To this end only a selection is presented here which should give a brief overview. While [Belis et al. \(2007\)](#) investigated the spherical cold bending of laminated glass panels, described the structural behaviour of double curved glass shells made of cold bent glass laminates. In both publications the cold bending of the glass panel itself and its structural use is mentioned. Mechanical fixing to the substructure in advance by using adhesives was not investigated. [Behr et al. \(1993\)](#) described the behaviour of laminated glass under lateral pressures, but not the cold bending process. [Feldmann et al. \(2014\)](#) wrote the Guidance for European Structural Design of Glass Components to fix the actual state of the art. [Galuppi and Royer-Carfagni \(2012\)](#) investigated the effective thickness of laminated glass. [Hooper \(1973\)](#) described as one of the first bending of laminated glass. Other previous studies about cold bent glass were done by [Eekhout \(2004\)](#), [Datsiou and Overend \(2016\)](#) and [Beer \(2013\)](#).

Regarding the use of structural adhesives for connection—an important part within this research—also a brief overview is given. The use of structural bonded joints as a connection of glass and metal is a topic within recent research projects. [Belis et al. \(2011\)](#), [Santarsiero and Louter \(2013\)](#) and [Overend et al. \(2011\)](#) investigated the use of structural bonding but not particularly for bonding of cold bent glass. In [Feldmann et al. \(2012\)](#) hybrid steel-glass beams were studied regarding load carrying capacity, stability behaviour, ductility and robustness. Again the adhesive bonding of cold bent glass was not investigated in detail. [Bucak et al. \(2007\)](#) studied the use of structural bonded steel-glass constructions. In [Richter et al. \(2014\)](#), the influence of multi-side bonding in structural bonded joints was investigated. Although the above mentioned research projects and publications provide a fundamental understanding of the use of cold bent glass and structural bonding itself, the use of structural adhesives to guarantee a mechanical fixing of cold bent glass to a metallic frame in advance and to build an innovative unitized cell was not focused at all.

The final objective of the European RFCS research project “S+G” is to develop a new generation of high performance steel-glass building skins that meets these

Table 1 Coefficient of thermal expansion [O’Brien \(2010\)](#)

Material	Thermal expansion at 100 °C [10 ⁻⁶ /°K]
Glass	9
Aluminium	24
Carbon steel	11.7
Austenitic stainless steel	16–17
Ferritic stainless steel	11.2–12.1
Superferritic stainless steel	10.3–11.2

requirements ([Royer-Carfagni et al. 2014](#); [Galuppi et al. 2014a,b](#)). The novel high performance building skins will be based on a unitized system of high quality steel alloy frames and glass panes where the steel sections are an integral and indispensable part of the system. In this research, one aim is to demonstrate that these new high performance skins could outperform the established metallic-framed building skins. The main challenge will be an enhanced structural efficiency. Regarding this point, the main objective is to achieve a composite action between steel or equivalent and glass by means of developing effective techniques utilising suitable adhesives for structural bonding the two materials. The material properties play an important role. For example, bonding between metals and glass can be achieved by means of high-strength adhesives. By considering materials with similar coefficients of thermal expansion, such as glass and steel in general, selecting optimal alloys and surface treatment for steel can enhance the durability of the bonded joint. Especially, a particular type of ferritic stainless steel (usually referred to as superferritic (i.e 470 LI EN 1.4613)) meets this requirement ([O’Brien 2010](#)). This allows for the possibility of bonding steel and glass by very thin films of adhesives, without incurring in excessive stress due to differential thermal expansion. Table 1 shows an overview of common coefficients of thermal expansion.

When addressing the versatility of the applications this can be achieved by exploiting the high stiffness of steel to provide a higher range of applications and architectural requirements, e.g. free-form surfaces by cold bending of glass. Concerning the cold bending, the structural properties of the bent laminated glass play an important role. Within several past research projects many tests on the behaviour of the laminated

glass were performed and numerical investigations as well analytical approaches were conducted (Feldmann et al. 2007). In this context it has to be mentioned that curvatures obtained by the usage of bent glass can have two benefits, on one hand bend glass fulfils obviously the aesthetical demand of the architects or designers. On the other hand, it should be mentioned that depending on the direction of loading in relation to the curvature, the stiffness resulting from the geometry can be much higher in comparison to flat glass. Within several research projects this phenomenon has been figured out by performing a large number of tests (i.e. Bucak et al. 2009; Ensslen et al. 2010). Regarding the process and the mechanical behaviour of cold bent glass panels, investigations have been done by Galuppi and Royer-Carfagni (2015) and Belis et al. (2007).

Regarding all the above mentioned details, seven partners with different expertise were involved in the research project to ensure high-quality and promising results: Universities: University of Parma (UPR), University of Pisa (UPI), University of Cambridge (UCA) and University of Aachen (RWTH); material producers: ThyssenKrupp Acciai Speciali Terni (TKL) and Dow Corning (DOC); building industry: Trimo (TRM). As a consulting partner the founder of the engineering office “Glass Light and Special Structures” Tim MacFarlane (GLaSS) is also involved in the project. In this paper the testing and results of eleven full scale prototypes and first numerical investigations under out-of-plane loading, which were performed by RWTH Aachen University, are presented.

1.2 Objective of experiments

Definition of requirements and potential markets for innovative building envelopes is a prerequisite for guiding the design of innovative high-performance building skins, with a view to an immediate marketing of an innovative product. The conception and realization of an interface fulfilling aesthetical, social and technical requirements are of prime importance.

The new system should address the needs of standardized flat surfaces, but it could be conveniently applied to free-form curved surfaces through the composition of steel with cold-formed-glass. The panelization of those surfaces with the unitized cells, which present no symmetry or repetitiveness, is perhaps the most challenging task in contemporary facade engi-

Fig. 1 Centre de Communication—Citroën, Paris: **a** view, **b** detail (Feldmann et al. 2006)

neering design. One positive aspect is the advanced computer-numerical-controlled production techniques, which enables construction of any type of surface. However, another aspects are the technical and financial efforts, which are extraordinary and often unacceptably high unless a sufficiently regular panelization is found. This can be achieved by using a finite number of different-in-type and different-in-size unitized cells, within the free-form surface.

If the glass panels are plane, the only possibility to approximate a curved surface is by means of standard faceted triangulated solutions (see Fig. 1) (Feldmann et al. 2006).

As the architectural trends are changing and smooth surfaces are always preferred, triangulated envelopes are no longer aesthetically appealing to many architects. For other textural forms, such as the hexagonal patterned, results are also very complicated to put into practice.

Figure 2 shows the starting point of the development within the project S+G. Here, a glass pane in a hyperbolic paraboloid shape is provided for the facade.

The angles between the various sides of the quadrilateral cells are not necessarily perpendicular, and this may increase the difficulty in glass cutting, steel junctions and panel assembly. The innovative systems envisaged in the project “S+G” were preferably based upon inclined frames obtained from a plane rectangle by a moderate out-of-plane displacement of one of the corners with respect to the other three, which then stay in one level horizontally. Since the opposite sides of

Fig. 2 **a** and **b** Starting point of developed innovative steel-glass composite system within project “S+G” (Royer-Carfagni et al. 2014)

the quadrilateral have the same length, the glass pane can be cold bent to the hyperbolic paraboloid shape by applying concentrated forces at its corners, fitting with the inclined rectangular metallic frame when opposite reaction forces are applied at one corner. Remarkably, such a surface retains rectilinear borders and fits with the inclined quadrilateral metallic frame, with opposite reaction forces applied at its corners, i.e. this innovative glass-steel composite system is compatible under reciprocal action of concentrated forces exchanged at the corners. The assembly of various panels, obtained from identical cells by simply varying the twisting angle between the sides, gives the desired surface.

Concave and convex surfaces can be built with planar quadrilaterals to obtain a faceted surface, but if perfect smoothness is essential, the elementary cell could be composed of slightly curved steel beams, and cold-formed-glass obtained through lamination. One of the most interesting features is the flexibility of the system. The frames may be all of one size, fitting to a curved surface by simply varying the twisting angle. This can be easily obtained if a proper frictional bolted unit with slotted holes is used to connect the four sides of the frame. Flat glass can be directly connected to the frame by a bonded joint. Afterwards the steel-glass composite system could be twisted conforming the curved profile of the roof and consequently the adhesive between glass pane and steel would subject to a complex stress state. As one additional innovation, the adhesive film transparent structural silicone dhesive (TSSA) (Hagl et al. 2012; Santarsiero et al. 2014) provided by Dow Corning is studied within the project.

The aim of investigations on adhesives was the determination of materials and surface treatment combinations providing the strongest and most durable bond. In conjunction with this particular design exercise, the

composite action of the steel and glass is studied to assess the bonding of rectangular steel frames to glass to create efficient composite panels that can be installed as unitized components for traditional planar facades. Structural adhesives are called the most important joining technology of the twentyfirst century. However, adhesives hide a very high complexity in themselves as visco-elasticity, chemical/physical dependent behaviour, Mullins-effect or compressibility to mention a few of them. Because of these complex properties, there were and are many ongoing and former research. For the investigations within this research project, it is very important to define that here the adhesives are a functional instrument to reach the aims. The surface treatment for the materials used and the selection of the most suitable adhesives for this innovative application are studied, but the adhesives themselves are not subject of this research.

1.3 Description of developed unitized cells

Within the project the idea was to design an innovative system for unitized steel-glass composite systems envelopes to meet architectural, energetic and technical requirements and to create a synergetic action of steel structural framing members with glass facade elements, which are easy to fabricate and applicate. One of the most challenging part within the innovative design is the demand of standardized flat surfaces but at the same time applied as free-form curved surfaces of the composition of steel with cold-formed glass. The chosen geometry for the elementary cell is a hyperbolic paraboloid. For these research issues, within the project three different kinds of innovative solutions for the unitized cell were developed: (1) TWIST (TWIsted

Fig. 3 **a** sketch and **b** corresponding realistic images of TWIST (1800 × 1800 mm), **c** sketch and **d** corresponding realistic images of HYP&R (1800 × 1800 mm) and **e** sketch and **f** corresponding realistic images of WING (1500 × 1500 mm)

SStructure) by University of Pisa; (2) HYP&R (HYPerbolic Paraboloid & Rotules) by University of Parma; (3) WING (WINGed Glass) by the engineering office “Glass Light and Special Structures”. All three types of unitized cells, where the glass lay-up was double laminated safety glass 66.4 with PVB, were structurally bonded first and the glass subsequently cold bent. For providing a first overview about the differences, Fig. 3 shows for all three specimens a sketch (upper line) and a picture of the finally realized prototype (lower line).

Overall, eleven specimens (cf. Table 4: one TWIST; six HYP&R; four WING) were tested to failure with the varying usage of the three different kinds of adhesives: TSSA (Transparent Silicone Structural Adhesive manufactured by Dow Corning), DC 993 (2C-structural silicone manufactured by Dow Corning) and Sika 265 (1C-polyurethane manufactured by Sika). These tests were also assessed for testing the ability of the glass panes to restraint the buckling of the steel members and to offer adequate constraint as fixing, also in the event of accidental breakage.

The first solution for the unitized cell (TWIST) consists in a self-supporting steel-glass structure, where the bonding connection between glass and steel was provided with the adhesive DC993. The analysed case study describes an 1800 × 1800 mm double curved steel-glass composite cell, made up of a laminated

toughened safety glass pane with a PVB polymeric interlayer, designed in order to satisfy the fail-safe design principles actually required for structural glass. The maximum deformation at the twisted corner is about 80 mm. The glass panel is bonded to an external frame of cold-formed stainless steel with a maximum thickness equal to 6.5 mm. Since the cold-formed glass panel remains in the elastic domain, the external frame structure is necessary to limit the maximum spring-back of the entire cell once that deformation is applied and, moreover, to guarantee the connection and assembly of adjacent cells, leading to various roof/facade surfaces. With this configuration the main advantage is, that once assembled, the TWIST cell could be considered “self-bearing” and used in deformed configuration with no need of an additional bearing structure. Frame and glass are connected through the adoption of a structural adhesive applied on borders: linear connections reduce the problem of high stresses generated typically of concentrated connection.

The second design is called HYP&R, which is characterized by a hyperboloid shape (HYP) with rotules (&R) on the frame. From the six specimens, there are three produced with DC 993, two with Sika 265 and one with TSSA. One side of the frame is directly connected by structural bonding to the glass panel (1800 mm × 1800 mm) during the deformation process leading to

Fig. 4 **a** and **b** Untwisted specimen HYP&R with Sika 265

the parabolic hyperboloid, while the other side of the framework will be further adapted to the deformed shape with the adoption of commercial rotules, opportunely designed to obtain the desired unit. The so-obtained cell is not self-supporting, so that it needs to be connected to a structural system. Figure 4 shows the untwisted specimen before the twisting step.

The third element was developed to study the possibility of creating a barrel vault structure using thin toughened glass panels 1500×1500 mm bonded to a frame, which is connected by hinges and so called wings to the substructure (WING). One Wing was produced with TSSA and the other one with Sika 265. The steel wings are hinged to facilitate the bonding process which is typically carried out in a vacuum bag where protruding local elements can pose a problem. The hinge connection also allows the panels to be joined together with splice bars at the corners at the correct angle. In order to create the curved shape, the glass panels will be twisted into position and the bonded joint of steel and glass will be designed to support the restoring forces generated by the twisted geometry. Therefore, the bonded joint of glass and steel has the double function of securing the glass to the steel frame firstly against wind suction and restoring forces and secondly in creating a composite section with the steel angle to resist bending forces in the barrel vault structure. In the following the work performed in S+G will be presented. The main objective are the component tests of the three different cells under out-of-plane and in-plane loading

to show the feasibility and opportunities of structural bonded cold bent glass elements.

2 Description of tests

2.1 Introduction

This chapter gives an overview about the planning, preliminary testing and performing of the different tests. As described before out-of-plane tests were performed at the testing lab of RWTH Aachen University. The out-of-plane tests are divided into a pressure setup (representing wind, snow, self-weight) with loading from the upper side and a uplift setup (wind suction) with loading from the lower side to simulate the different cases of loading. Here, it is important to mention, that the cold bending is done in the same direction for both load cases. At the beginning of planning the tests, the specimen had a hyperbolic paraboloid shape. Therefore, the load direction would not have an influence. Because of the difficult issue of cold bending the glass panel into a hyperbolic paraboloid shape, the cold bending was finally done by fixing three corners and deform the fourth corner about the complete deformation. Thus, for pressure tests the corner is deformed in the same direction and for suction tests in the opposite direction related to the load.

Apart from that, the three different prototypes, each of them manufactured with one or more of the three different adhesives were tested. In Table 2, the testing

Table 2 Experimental matrix with the variation of the testing parameters

Specimen type	TWIST			HYP&R			WING		
	Sika	DC993	TSSA	Sika	DC993	TSSA	Sika	DC993	TSSA
Out-of-plane setup, pressure		1		1	1	1			
Out-of-plane setup, suction				1	2		2	1	1

Table 3 Adhesive material: properties and FE-modelling (Dow Corning 2013, 2014; Sika Deutschland GmbH 2012; Royer-Carfagni et al. 2014)

Adhesive	Components	Potlife (min)	Elongation break (%)	Elastic modulus (MPa)	Poisson's ratio (–)	Shear modulus (MPa)	Nom. thick-ness (mm)	Surface cleaning (–)	Primer (–)
DC993	2	10–30	250	2.5	0.4999	0.47	6	Dow Cor-ning R40	–
TSSA	Film	Auto-clave	250	9	0.4999	2.5	1	Dow Cor-ning R40	–
SIKA	1	10–20	350	6	≈0.48	0.7	6	Acetone/isopropanol	Sika Primer 206 G+P

Fig. 5 FE-model of quadrilateral unitized cell prototype with a hyperbolic paraboloid shape (displacement scaling: factor 10): **a** original planning of hyperbolic paraboloid form, **b** transposed form within S+G with maximum displacement (*blue*) of 80 mm

matrix of the prototypes and the variation of testing parameters is presented. The total number of specimens is eleven. Furthermore, it must be mentioned that with variation of the adhesive the bonded area on the steel frame also varies, because of design and application limits, which has an influence on the results.

The characteristic material properties of the used adhesives are given in Table 3. The bonding process of the specimens within this project was done by partners of the project. They are professional producers: Dow Corning as adhesive manufacturer and Trimo as a facade producer.

First of all, preliminary outputs within the project were used to develop a numerical model capable of prediction of the expected behaviour and loading of the cells to be tested. A detailed description of the numerical model and calculation method is presented in Chap. 4. The numerical models were improved by the knowledge obtained in the characterization of the adhesives, which in the project was done by Dow Corning (Royer-Carfagni et al. 2014). The numerical modelling in advance was used to determine the required amount and positions of measurements (cf. Chap. 2.2) during the tests with regard to obtain the necessary parameters

for the verification and final improvement of the testing set-up.

The numerical simulations were performed in two steps: first, the cell has been twisted by deforming one corner's displacement of 80 mm as it is performed in the tests; in the second step the cell has been loaded up to a certain load.

Figure 5a shows the FE-model of the quadrilateral unitized cell prototype with a hyperbolic paraboloid shape. Because of realization issues of a hyperbolic paraboloid form (Fig. 5a), within the project S+G, UCA investigated and verified the opportunity to twist the cells in a similar manner by deforming one corner and fix the other three (Fig. 5b) (Royer-Carfagni et al. 2014).

2.2 Testing setup

In the following, the detailed procedure for the described experiments is explained. The first task was finding the best test setup for applying an equal loading over a majority of the glass panel, which at the same time adapts to the twisted area without causing stress

Fig. 6 Sketch of load application by lifting bags

concentrations. One difficulty was to generate a regularly distributed surface load on the deformed curved surface of the cold bent glass plate, which could finally be realised through a multiply-hinged connection to the loading jack.

The most effective and due to FE simulations reproducible way of providing an equal out-of-plane loading which was high enough to cause a failure of the laminated glass pane, was by using so called lifting bags. These lifting bags were filled with air and had a size of 1000 mm × 300 mm (empty). An experimental and numerical study was performed to determine corresponding loading area of the lifting bags, depending on the air pressure and the loading with the hydraulic loading jack, as basis for the verification by FEM. Loading applied by lifting bags offered within the project the best possibility to load all panels in a same way, so that the loading area is clearly defined and reproducible. This was an important aspect allowing for numerical calculations to be done by applying the same loading area. This leads to a good comparability and thus to a possibility to derive design rules and guidelines, which then can lead to a correlation to in-service life conditions.

Using a hydraulic loading jack and the combination of load distribution beams an equal loading over the whole glass pane could be achieved. The hydraulic loading jack and the load distribution beams were built with a multi-hinged support so that restraints could be

Fig. 7 Exemplary distribution of principle stress of HYP&R cell for positions of measurements (loaded side for twisting and loading)

avoided. Figure 6 shows the principal sketch of the load application by lifting bags.

Independent from the chosen loading system (pressure or suction), the first step was twisting the prototypes, which was done in the following way: Each prototype was twisted according to the maximum capacity of each specimen due to pushing down one corner, while the other three were kept fixed. The second

step was positioning and filling the lifting bags and the third step was the displacement controlled loading by the hydraulic jack with a defined loading velocity of 1 mm/min. Before deforming the test specimen, strain gauge rosettes for the glass panel and displacement transducers were applied to measure the strain and the deformation during the cold bending.

The preliminary linear numerical simulations of the tests were conducted in order to determine the positions of the measurement devices, necessary to obtain sufficient information for later verification of the test results. These simulations, performed using TSSA properties, were also used to improve the final realisation of the test setup. These preliminary simulations assumed linear-elastic behaviour of all components; for modelling the TSSA, the values from Table 3 were used. Figure 7 shows exemplary the numerical results of the cell at loaded side (twisting and loading), displayed as the highest principle stress. For the glass, the highest stresses are observed in the middle of the panel in contrary to the load acting direction and in the edges, where the glass corner of the panel is twisted.

In order to get detailed information on the behaviour of the cell during the twisting and later on during the loading, the following measurement devices were installed (cf. Fig. 8): For the first test, four displacement transducers and 12 strain gauge (SG) rosettes were applied. The displacement transducers (DT) were located vertically in the twisted corner, in the middle of the plate and horizontally on two sides (DT 1 and DT 2, cf. Fig. 8) to measure possible horizontal deformation of the glass plate. After the first test was evaluated, a reduction of the measuring device was possible. Here three strain gauge rosettes and two displacement trans-

ducers were applied at the most striking points. One DT and SG rosettes in the middle of the glass panel and one SG rosette at the twisted edge.

Figure 9 shows the final test setup for the case “pressure” for a HYP&R- (a) and a TWIST-element (b). The prototypes are already twisted and the measurement devices are installed. Four lifting bags for each test are used, regularly distributed over the width of the element. With a width of 1.80 m for the HYP&R- and TWIST-elements the choice of four lifting bags was the best way to generate a loading equally distributed over the majority of the glass panel area.

The testing setups for the out-of-plane experiments representing wind suction loading are shown in Fig. 10. The whole elements were twisted in the first step, the same way as explained above, and after that turned around in order to apply the reverse (suction) loading. Due to the smaller size of the WING-elements (with od 1.50 m) only two lifting bags were used for an equally distributed loading.

As shown in Figs. 9 and 10, for both specimens HYP&R and WING, a substructure had to be designed and built, because these two types of unitized cells were not designed as self-supporting steel-glass structures.

All tests were performed in three steps. After all necessary measuring devices were applied, first of all one corner of the unitized cell was cold-formed while the other three were kept fixed. During the cold bending all strains and the deformation in the middle of the plate were measured. In the next step the lifting bags were brought up to the glass panels and filled in a controlled way, so that every lifting bag had the same filling volume (0.3 bar) and consequently was able to transfer the same loading in this loading area. Afterwards

Fig. 8 a and b Measuring equipment using example of a HYP&R specimen

Fig. 9 Pictures of the out-of-plane testing setups, pressure: **a** HYP&R+Sika, **b** TWIST+DC993

Fig. 10 Pictures of the out-of-plane testing setups, suction: **a** HYP&R+Sika, **b** WING+Sika

the displacement controlled load was applied with the defined loading velocity of 1 mm/min. The chosen loading velocity was the same for all specimens in order to avoid any influence of the deformation velocity on the test results.

3 Results of experimental investigation

3.1 Introduction

The following chapter presents the most important results of the experimental investigation. Because of the different types of specimens and the differing adhe-

sives it is complex to fit and to compare the results in detail, but the idea of the project was to have a wide range of results and performance indications allowing to prove the basic feasibility, especially mechanically, of the different unitized cells. Due to the big variation between the different specimens, the results give a very good overview about different behaviour depending of different configurations.

Foremost the global behaviour of the steel-glass composite system in terms of the absolute fracture load (Chap. 3.2) and the global load-displacement curves (Chap. 3.3) are presented. As part of the tests on HYP&R, tensile tests on single rotules, which are the main characteristic parts of the HYP&R specimen,

Table 4 Results of the out-of-plane tests (load step 2 and 3)

Test	Prototype	Adhesive	Nominal bonding area (m ²)	Load direction	Max. load (kN)	Displacement (mm)	Mode of failure (–)
1	TWIST	DC993	0.42	Pressure	90.2	55.4	Glass
2	HYP&R	Sika	0.58	Pressure	27.4	29.8	Glass
3	HYP&R	DC993	0.58	Pressure	45.9	39.1	Glass
4	HYP&R	TSSA	0.32	Pressure	25.7	31.4	Glass
5	HYP&R	DC993_01	0.58	Suction	44.6	45.8	Glass
6	HYP&R	DC993_02	0.58	Suction	38.9	34.9	Glass
7	HYP&R	Sika	0.58	Suction	44.2	40.8	Glass/adhesive at glass (af)/ rotule
8	WING	Sika_01	0.18	Suction	46.3	52.8	Glass
9	WING	Sika_02	0.18	Suction	52.8	62.5	Adhesive(cf)
10	WING	TSSA	0.18	Suction	34.2*	34.2	Adhesive (cf/af at glass)
11	WING	DC993	0.18	Suction	19.8*	31.5	Adhesive at steel (af)

* Failure only of adhesive, no glass failure

af adhesive failure, cf cohesive failure

were performed to investigate their strength (Chap. 3.4).

3.2 Failure modes

Eleven prototypes were tested to failure. Due to their structural composition different fracture loadings and failure modes could be observed. Table 4 shows the different prototypes and their fracture loadings with the corresponding adhesive, nominal bonded area and the tested loading direction. The resulting maximum loads were measured by a load cell at the hydraulic jack and the resulting displacement by the displacement transducer in the middle of the glass panel. Table 4 includes the deformations measured during the step two (filling of lifting bags) and step 3 (loading). The deformation for step one (cold bending) with 5–6 mm is not included in Table 4.

The performance of the specimens varies significantly regarding the mode of failure. It should be noted, that this is depending on the load case and the prototype, especially when regarding the different parameters characterising each structural component. Often the glass was the critical element of the composition, but it failed in different ways, particularly at different locations. For the HYP&R the glass failure is above the rotules. For WING it was nearby the hinges and for TWIST at the cold bent corner of the glass. As

described before, also two different loading directions were applied to the specimen; this affects directly the fracture of the unitized cell. With the load case pressure, the higher stiffness of the glass through the cold bending and the influence on the adhesive is studied. The load case suction is critical for the glass and the adhesive: glass is loaded superimposed to cold bending, because the loading is on the concave surface and adhesive needs to resist tensile stresses, which are the critical kind of loading. Furthermore, the three different adhesives were investigated regarding their feasibility and suitability for the application in the unitized cells. In the following, each specimen type is described according to the failure mode that was observed.

As mentioned before the main characteristic part of the HYP&R test specimen are the rotules, which were mechanically connected to the steel sheets, and then bonded with an adhesive to the glass. The HYP&R cell was tested with all three different adhesives. With regard to the failure mode, all specimens tested in direction of pressure and the two specimen manufactured with DC 993 and tested under suction exhibited glass failure directly over one rotule, where local stresses in the glass caused by the clamping effect are very high. During the loading the edges of the glass panel between each rotules show high deformations, a stress concentration on the upper side of the glass panel over the rotules develops (see Fig. 11) which consequently leads to the main failure of the glass panel (see Fig. 12).

Fig. 11 a and b Deflection of glass pane on the edges

Fig. 12 a and b Fracture pattern of the HYP&R specimen in a pressure loading direction b suction loading

Fig. 13 a and b Fracture pattern of the HYP&R+Sika specimen in suction loading

Because of this issue, the rotules were also tested separately (cf. Chap. 3.4).

Contemplating the test performed with suction loading on HYP&R+Sika, a different failure mode was observed. Here an adhesive failure at the glass surface of the adhesive, of one rotule and also of the glass panel was detected (Fig. 13). As the fracture occurs fast and spontaneous, the exact location of the first failure could not be identified. One reason for the failure of the adhesive could be the difficult manufacturing of one-component adhesives. This includes the possibility, that the selected specific curing period did not fit the width of the adhesive connection of approximately 85 mm.

As mentioned before the fracture of the glass panel is dependent on the system parameters. The WING specimens for example exhibit a smaller bonded area than the

other prototypes. In these cells the glass-to-steel bond is vulnerable towards suction. In addition to that, the steel frame, which is bonded to the glass panel, has a concentrated connections, similar to the rotules at HYP&R specimen, to the steel wings, which are connected to the framework. Consequently, during the deformation of these cells the behaviour could be characterized like that of the single supported cells of HYP&R. Therefore, two types of fracture modes could be observed on the WING cells, which could be attributed to the different adhesive applied on the specimens. The WING cell produced with 2C silicon DC993, with TSSA and one with Sika 265 exhibited adhesive failure at the glass surface with no glass fracture (Fig. 14). For suction loading, the adhesive and so the structural connection of the steel-glass composite is the critical part, which determines the maximum load capacity.

Fig. 14 a and b Fracture pattern of the WING+TSSA specimen in suction loading

Fig. 15 a and b Fracture pattern of the WING+Sika specimen in suction loading.

Fig. 16 a and b Fracture pattern of the TWIST

The other WING bonded with Sika 265 lead to a fracture of the glass due to the stress concentration on one single point of connection to the frame (Fig. 15).

The main difference of TWIST compared to the construction of HYP&R and WING cell is, that the prototype is realised with a linear bonding area and thus a flat boundary condition around the whole glass. Concerning the failure mode, it means that as expected before, the failure mode changes because of avoiding stress concentration about single points under pressure loading. So that on TWIST the glass has broken on the lower glass panel on the twisted edge due to high strength (see Fig. 16).

3.3 Load-displacement curves

As described before the tests were performed in three steps: 1. Twisting of the cells through cold bending (HYP&R: fixing of rotules on supporting frame; WING: fixing of bolts on supporting frame; TWIST: through self-weight); 2. Applying the lifting bags and run-up the position of loading jack before starting the actual testing; 3. Testing by increasing the load up to failure. Figure 17 shows exemplary the displacement-time graph measured in the middle of the glass panel of all three steps for test of HYP&R+DC993 under pressure loading by displacement transducers. Almost 16% of the final fracture displacement is caused by the twisting in step one, while at least additional 36% are obtained by applying the weight of the lifting bags and load distribution beams. That means the half of the resulting displacement is caused due to step one and two.

In the following load-displacement graphs of out-of-plane tests are presented and compared in critical points for the displacement transducer in the middle of the glass panel. The displacement transducer was installed after the twisting of the element for measuring the displacement until the breakage of the glass. First of

Fig. 17 Stepwise displacement-time curve for three loading steps exemplary for test HYP&R+DC993 (pressure)

all, it makes sense to compare the different load cases, pressure and suction, because of the opposite direction of cold bending as described before.

The dashed lines in Fig. 18a show the results of the tests with suction loading, the continuous lines represent the results for the pressure tests. Obviously the dashed lines increase with a smaller slope than the continuous lines, which means, that the displacement of the suction loading is smaller than for pressure loading for the same load. For this reason it is clear, that the prototypes tested with pressure load are based on a system with a higher stiffness, because the curvature of the specimen is convex against the load direction. For suction tests, the curvature is concave to the loading direction, which leads to a weaker system behaviour.

For evaluation it is important to discuss the position of the steel frame (pressure and tensile stress in the adhesive) and the curvature direction of the glass.

For adhesives in general tensile loading is more severe. That means that the suction load case is more critical, which subsequently is demonstrated by the failure of adhesive (adhesive or cohesive) in four of seven specimens. Additionally, as described before, the suction loading case is also critical for the glass.

When regarding pressure loading the dominating part for the stiffness of the bonded steel-glass composite system is the bent glass. Only the HYP&R specimen produced with TSSA under pressure shows a lower stiffness than the other tests, which does not correlate to the property of the adhesive TSSA with the highest stiffness and smallest layer thickness (1–2 mm, against DC993 and Sika with 6 mm). Considering that there is mostly only one specimen per type and that the result is contradicting to expected behaviour, it is obvious that this has to be studied by further tests. Also, there are many different influence factors combined: cold bending, stress through cold bending process in adhesive, adhesive layer, curvature, which makes it difficult to identify the effects resulting from each influence factor without additional tests investigating separately the influence of each factor.

The HYP&R and the TWIST specimens were produced with the same glass thickness and dimensions. Additionally, the cold bending was done with the same deformation of the corner. Taking all this into consideration, it is obvious, that under pressure both specimen exhibit the same stiffness (cf. Fig. 18b). The TWIST shows the highest load capacity due to the self-supporting structure. In case of suction the lower glass in the HYP&R is loaded and pressed away from the steel frame, which leads to high tensile stresses in

Fig. 18 **a** Comparison of the load-displacement curves with different load cases and **b** load-displacement diagram for all tests with load case pressure

Fig. 19 **a** Load-displacement diagram for all HYP&R tests with load case suction, **b** load-displacement diagram for all WING tests with load case suction

the adhesive. This results in a different stiffness of the system of the element compared with HYP&R under pressure loading. The size of the area of the adhesive is in that case nearly the half of the pressure tests with DC993 or Sika.

Figure 19 shows the load-displacement curves under suction loading for (a) the HYP&R specimen (two with DC993 and one with Sika 265) and (b) the four WING specimen manufactured with Sika 265, DC 993(2×) and TSSA. The curves for HYP&R show an equal course, which shows, that the influence of the two different adhesives is very small in this big specimen, when they are correctly produced. The dominating parameter of the system stiffness is the glass stiffness, which is mostly determined by the thickness of the glass panes. Also, the possible reproducibility is shown, because the two curves of the DC993 are more or less the same. The slightly smaller stiffness of the Sika specimen, which occurs after the first failure, could be explained through the different fracture mode of the Sika 265 (glass, adhesive, rotule) compared to the DC993 (glass). For the two HYP&R specimen with DC993 glass failure could be observed. Within the Sika 265 test a combination of glass, adhesive and rotule was observed. Regarding the graph in comparison to the two HYP&R with DC993, the first failure occurs probably in the glass. The failure of the adhesive and the rotule is the result of the glass failure.

For the four WING specimen under suction loading (cf. Fig. 19b), there is a high deviation between the results, regarding the failure mode and the different kind of adhesive. Here, the TSSA, as expected, exhibits the highest stiffness. When regarding the failure mode

of WING+TSSA, it is noticed that the TSSA with a very thin layer (around 1 mm) has a big influence on the system behaviour, because there is less possibility for deformation like for the test with nominal 6 mm thick layer of Sika 265. The two WING specimen produced with Sika 265 have a quite equal behaviour, although they had a different failure (glass and adhesion at glass surface). The WING+DC993 is a little bit outstanding. Only at the beginning the stiffness is similar to the WING+Sika as it can be observed for the HYP&R tests, but then the WING+DC993 exhibits an unexpected behaviour, which can be clarified by additional tests only.

3.4 Tests on rotules

The main characteristic of the prototype HYP&R are the rotules, which should on the one hand be used as a tool for twisting the glass panel and on the other hand for fixing the whole element into the bearing structure during tensile loading. As seen in the tests, the glass failure occurred above the rotules through the fixing point effect implying a high level of loading on the rotules. Because of that, the rotules were specially tested alone (see Fig. 20) in order to measure the fraction load of each rotule. The fixing to the frame was carried out at the production in two different ways: The rotules were either welded or bolted to the steel frame. After performing the out-of-plane tests, six welded and six bolted rotules were cut out from the steel frame and tested as shown in Fig. 20.

Fig. 20 a and b Pictures of the testing setups for the rotules of the HYP&R-element

Fig. 21 Failure of the rotules. a failure of the screw. b failure of the welding

In the experiments, the following results were obtained: it can be distinguished between two different kinds of failure as shown in Fig. 21. Most of the rotules broke due to the failure of the bolt and only one because of failure of the welding. Overall, the maximum load was determined to around 11 kN at a deformation of 5 mm for the welded rotules and around 15 kN with a deformation of 5.5 mm for the bolted rotules, with nearly the same development in the force-displacement curves for each type.

Figure 22 shows the results of the tensile tests for selected elements in a force-displacement diagram. The dashed lines represent the testing of the bolted rotules and the dotted lines the tensile behaviour for the welded ones. All of them demonstrate the failure of the bolt inside of the bearing. The bolts contribute to a greater stiffness of the rotule than the welds. The maximum load is more than 2 kN higher and the failure occurs later. The continuous line depicts another mode of failure, the tearing of the weld. The failure in that case appears suddenly and the rotule is unable to take further load. The results show, that the rotules and the connec-

Fig. 22 Force-displacement curve for the tensile tests of the HYP&R-rotules

tion has high load capacities, so that for the HYP&R specimen, the glass is the critical part of the steel-glass composite.

4 Numerical investigation

4.1 Presentation of the model and method (linear elastic)

This chapter presents first numerical calculations as linear analyses based on the results of the experimental investigations. Because the project has not been completed yet, there will be further numerical studies considering geometrical and material non-linearity, see Chap. 5.

The finite element modelling of the tests is done with ANSYS classic 15.0 as a static analysis. Figure 23 shows the used mesh size in the FEA in detail (a) and global (b) for all specimen. In the area of the bonded joint, the mesh was refined, accounting for higher stress gradients. The refinement of the model,

Fig. 23 Discretization used for numerical studies: **a** detail, **b** whole model

i.e. the number of necessary elements, was studied by a convergence analysis. The boundary conditions were set in accordance to the real testing setup. For the here described first investigations, it is assumed, that the material behaviour is linear-elastic and determined by the modulus of elasticity E , the shear modulus G and the Poisson's ratio ν , implemented in ANSYS. The glass was modelled monolithic with the nominal thickness. The material properties, which were used to model the adhesives, are shown in Table 3.

For modelling the specimens three-dimensional continuum elements were used, Solid185 (8-node hexaeder-element) for glass and steel and Solid186 (20-node hexaeder-element) for the adhesive layer. Although the choice of Solid186 elements causes a higher computational effort, there is the advantage of getting a better calculation quality.

Three different loads were applied to the system: the self-weight, the twisting and the loading. The bearing is dependent on the construction of the cell. In case of the HYP&R-elements a concentrated bearing was supposed corresponding to the area size of the rotules. In the modelling of the concentrated bearing for the WING-elements an area size was chosen which corresponds to the hinges of the WING. As for the prototype TWIST the glass panel was connected directly to a hollow profile, it was assumed to be a small flat bearing.

4.2 Load-displacement curves

The program distinguishes two different load steps (step 1 twisting and step 2 applying the load) and gives consequently results as displacements or stresses. First of all, the temporal evolution of the displacement is dis-

cussed: In the experiment, the prototypes were loaded after twisting and the displacement is measured from the beginning of loading time. The total measured displacement consists of two components. The first one is formed during filling of the lifting bags and the resulting contact between load application and glass panel, while the second component is the consequence of the increasing load.

Figure 24 shows the variation of the displacement in z -direction (here exemplary model of TWIST) over the surface of the glass just for these two load steps and a pressure loading with a positive value in z -direction. For the load case pressure, the twisting and loading act in the same direction. Figure 24a shows the twisting step, where one corner is deformed about 80 mm and the other three kept at 0 mm. In Fig. 24b the resulting deformation from twisting and then loading is displayed. So, the convex cold bent glass is deformed in negative z -direction. There is a high deformation (blue) in the direction of the twisted corner.

For the load case suction, shown in Fig. 25, the changing of the displacement by the application of the load is different after load step two, because the loads are applied now in the opposite direction. The deformation in Fig. 25a is the same as in Fig. 24a. But in Fig. 25b, the legend differs, because the maximum changes from 0 to 40 mm, as the load is applied in the opposite direction of the curvature (in concave direction). Now, there is a high deformation (red) in direction of the fixed corner, which is oriented against the deformation of the twisted corner. These two examples verify, that there is a superposition, which has to be studied in future approach within the project.

To compare the tests carried out with the numerical results, the measured displacements in the middle of

Fig. 24 Exemplary results of the displacement (mm) in z-direction at TWIST, load case pressure **a** after twisting, **b** after loading

Fig. 25 Exemplary results of the displacement (mm) in z-direction at TWIST, load case suction **a** after twisting, **b** after loading

the glass after twisting and the values calculated by ANSYS are listed in Table 5. Regarding Table 5, the absolute value of the displacement calculated with the equivalent force, which is gained from the experimental investigations, can be evaluated for linear analyses by FE. Because the filling of the lifting bags cannot be simulated by FE in an easy way, only the displacement of the loading step is compared at this stage.

The occurring deviation to the measured displacement for the loading step, shows for linear elastic analyses a quite good agreement. The most accurate results are obtained for the WING specimen (10–20 %), which could be expected, because there the adhesives have a bigger influence. For the HYP&R under suction, the

same results could be observed. For the TWIST and the HYPER+TSSA, there are the highest deviations with 46 and 34 %. For HYPER+DC993, there is a very exact result.

The results show for absolute values of the experimental displacement compared to the numerical displacement calculated with the same loading in the middle of the glass panel, that the linear-elastic numerical modelling of the adhesive already gives good correlation of the deformation for a few configurations, especially under suction loading.

Figure 26 shows the comparison of the global behaviour of the experimental and numerical results as load-displacement curves. First of all, all numerical results

Table 5 Comparison between the experimental and the numerical displacement (only load step 3)

Test	Prototype	Adhesive	Load direction	Experimental displacement (mm)	Numerical displacement (mm)	Deviation (%)
1	TWIST	DC993	Pressure	43.1	57.7	34
2	HYP&R	Sika	Pressure	16.7	12.3	26
3	HYP&R	DC993	P	25.9	26.0	0
4	HYP&R	TSSA	Pressure	22.4	12.0	46
5	HYP&R	DC993_01	Suction	35.2	29.2	17
6	HYP&R	DC993_02	Suction	31.9	26.0	18
7	HYP&R	Sika	Suction	34.3	26.8	22
8	WING	Sika_01	Suction	43.5	47.9	10
9	WING	Sika_02	Suction	62.5	59.3	5
10	WING	TSSA	Suction	29.0	23.8	18
11	WING	DC993	Suction	31.5	23.9	24

Fig. 26 Comparison of experimental and numerical load-displacement curves of **a** HYP&R (suction), **b** WING (suction), **c** HYP&R (pressure)

show linear behaviour because of the linear material properties as input. In Fig. 26a for the HYP&R specimen under suction loading, the FE calculations confirm the experimental results in general. Also the

results of the two HYP&R+DC993 are very close together and the results of the HYP&R+Sika exhibits a higher stiffness than the two HYP&R+DC993, what is expected through higher stiffness of adhesive

and same nominal layer thicknesses compared to the DC 993.

Figure 26b shows the experimental and numerical results for the four WINGs under suction loading. There, the numerical results show for the two specimen with DC 993 and TSSA a similar good correlation as for HYP&R under suction, because the adhesives have a higher influence on the system behaviour as for pressure. For the two specimen with Sika only the stiffness at the beginning (up to 5 mm) have a good correlation, but beyond there occurs a high deviation.

For HYP&R specimen under pressure (cf. Fig. 26c), the results also show in case of linear elastic simulations a quite good correlation of the results. Here, also the deviation within the experimental results of the TSSA can be observed. The numerical curve of the TSSA is higher than the other two numerical calculations, what would be also expected for the experimental results. So, the experimental results seem to be too weak, because of problems with this test i.e. regarding boundary conditions.

Finally, all numerical results show, that the global behaviour could be modelled in a quite good correlation by only linear elastic numerical calculations. So, in the future work within the project S+G, the accuracy is expected to increase by using geometrical and material non-linear analyses.

5 Summary and outlook

Within the research project S+G (Steel+Glass) funded by the RFCS, a unitized cell for high-performance skins combining glass and metal using adhesive junctions, by fulfilling at the same time structural as well as energetic criteria, has to be developed. Consequently, regarding these research issues three different kind of solutions were developed.

In the presented paper, the main objective was to present the performance of out-of-plane tests on eleven specimens. Here the cells TWIST, HYP&R, and WING were tested until failure for two loading cases (pressure and suction). The cells showed different parameters as for example three different types of adhesive, TSSA (Transparent Silicone Structural Adhesive manufactured by Dow Corning), DC 993 (2C-structural silicone manufactured by Dow Corning) and Sika 265 (1C-polyurethane manufactured by Sika) as well as dif-

ferent geometries of the cell itself (i.e. width and length of cell, width and thickness of adhesive, etc.).

According to the test results, on seven of eleven specimen glass failure was observed, which depends on the type of specimen: For the HYP&R the glass failure is above the rotules. For WING it was nearby the hinges and for TWIST at the cold bent corner of the glass. Another failure mode observed (HYP & R+SIKA) was the combined failure of the glass, the adhesive and a rotule. As for glass components the failure happens very fast and spontaneous the failure initiation couldn't be observed precisely. The third failure mode was observed on the other three cells under wind suction, which shows pure failure in the adhesive (cohesive, adhesive and mixing of both).

The evaluation of the load-displacement curves exhibit a scattering and one of the main conspicuousness was the behaviour of the HYP&R+ TSSA, because the system stiffness is lower than the other tests, although the adhesives Sika and DC 993 have higher stiffnesses themselves. Because of the low number of tests per type, a statistical evaluation is not possible, which subsequently would give more information of each cell.

Regarding the numerical calculations, the linear-elastic calculation leads here for the cells under suction loading to a good and mostly conservative correlation.

As a next step, the obtained results will be evaluated and interpreted with regard to input parameters for the numerical models, especially by modelling the adhesive behaviour by non-linear material models and considering geometrical non-linearity. This will allow studying not only the global behaviour as done in this work, but closer the local behaviour of the adhesive and the stress state within the adhesive. The stresses measured in the tests will be used to calibrate the numerical models. In the current state, the WING could be the best prototype, because it is filigree and the cold bending could be done in a quite easy manner in comparison to the HYP&R and the relatively voluminous TWIST. Concerning the feasibility and suitability of the three different kind of adhesives, the results of these not statistically confirmed tests show that the best selection is the DC993. For the load case "wind suction", which is critical for the adhesive, the overall failure was only cohesive within the adhesive. For load case "pressure" the adhesive offered no changes in the behaviour.

With that data, the numerical models could be finalized and a case study could be started. In the next step

with all the data obtained the detailed model of the cells could be transferred into a simpler model of the mechanical properties of one cell. Using this model the mechanical performance of a complex multi-cell shape will be then investigated. To ensure redundancy and robustness of the system the performance of the complex shell in case of breakage of one cell (partially or completely) will also be assessed.

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