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CONTINUOUS BOND BETWEEN GLASS AND STEEL BY MEANS OF UHPC

Dorota PŁÓCIENNIK*

* Faculty of Civil Engineering, The Graz University of Technology, Lessingstraße 25, 8010 Graz, Austria
E-mail address: *dotap@sbox.tugraz.at*

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Abstract

At present the application of structural glass in architecture is usually characterised by structural combinations of steel and glass. The use of point supporting connectors is typical for this kind of mixed building technology. Because brittle materials do not stand up well to stress peaks, the capacity of load transmission via the connector must be improved with elastic interlayers or by a high-quality fit between the glass hole and the connector shaft. Thus the load is transferred along the boundary of the hole as well as via bearing pressure. However, the high in-plane shear capacity of glass panes cannot entirely be exploited by the use of point supporting connectors. This paper presents a new solution based on a linear continuous bond connection between glass and steel. This solution works with a third material between steel and glass. This material transmits shear loads from glass to steel via the bond between both materials. It turns out that Ultra High Performance Fibre Reinforced Concrete (UHPFRC) satisfies the strict requirements for such a bonding material. In order to get a sufficient bonding effect between glass and UHPC, the glass surface in contact is pre-treated in the following way: first enamel paint is mixed with quartz sand, then this mix is brushed onto the glass surface, and finally the glass is annealed. The outcome is a rough surface very similar to abrasive paper. A series of experiments have shown that this method of pre-treatment yields the best bond between glass and UHPC. The bond between UHPC and steel is dealt with in various publications and is considered to be sufficient. The Graz University of Technology is currently completing a project dealing with adhesive bonds between UHPC and construction materials. Glass-steel composite technology offers a wide range of new possibilities for designing modern, transparent and representative steel structures.

Streszczenie

Dzisiejsza architektura stosuje szkło konstrukcyjne najczęściej w rozwiązaniach mieszanych, zespolonych. Jako środek łączący wykorzystywane są najczęściej łączniki punktowe. W przypadku materiału tak kruchego jak szkło, miejscowe spiętrzenie naprężeń jest „źle znoszone“, a wynika z konieczność przenoszenia sił poprzez krawędzie otworów w szkle. W celu zmniejszenia koncentracji naprężeń otwory wyłożone są gumowymi pierścieniami, pozwalającymi na ich równomierne rozłożenie. W ten sposób siła skupiona w punkcie podparcia przełożona zostaje na obciążenie liniowe (po obwodzie otworu). W przypadku podparć punktowych wysoki potencjał, jaki leży w tarczowej pracy szyb, nie da się w pełni wykorzystać. Celem badań jest poszukiwanie nowych możliwości osiągnięcia połączenia liniowego ciągłego między szklanymi i stalowymi elementami konstrukcji. Cechą takiego sposobu przekazywania sił jest to, że naprężenia w połączeniu nie są bezpośrednio przenoszone ze szkła na stal, lecz pośrednio poprzez medium wypełniające profil stalowy. W wyniku poszukiwań odpowiedniego medium ustalono, że UHPFRC (Ultra High Performance Fibre Reinforced Concrete) spełnia te wysokie wymagania stawiane materiałowi łączącemu. Aby osiągnąć wystarczające zespolenie między szkłem i UHPC, konieczne jest odpowiednie przygotowanie powierzchni szkła w obszarze kontaktu z betonem. W tym celu na powierzchnię niehartownej szyby zostaje naniesiona farba emaliowa zmieszana z piaskiem wysokiej twardości (korundowym, kwarcowym, basaltowym, granatu). Podczas procesu hartowania piasek wtapia się częściowo w powierzchnie szkła, która przybiera wygląd i chropowatość papieru ściernego. Krawędź szkła, przygotowaną w wyżej opisany sposób umieszcza się w formie i zalewa świeżym betonem. Experymenty potwierdzają, że uzyskane w ten sposób zespolenie między szkłem i betonem wypełnia stawiane połączeniu wymagania. Typowe dotychczasowe zastosowania szkła jako elementu nośnego konstrukcji to dźwigary dachowe z pasmami stalowymi i środnikiem ze szkła, przeźroczyste, statycznie nośne poręcze schodów, szklane belki-ściany, które są obciążone np. na nich leżącymi płytami stropowymi, mosty-łączniki ze szkła między sąsiednimi budynkami, samonośne szklane wieże wyciągowe dla wind itp. Budownictwo zespolone szklano-stalowe otwiera nowe możliwości projektantom specjalizującym się w architekturze przeźroczystych budowli ze szkła.

Keywords: **Composite structures; Experimental analysis; Glass; High Performance Fibre Reinforced Concrete.**

1. INTRODUCTION

The main subject of this seminar paper is glass, which has been used more and more frequently as a primary supporting element in construction for the last century. Glass beams are used increasingly in the structural design of representative building and conversion projects. Glass elements are employed not only to enclose areas but also as structural supporting elements. Here beams made of laminated safety glass are increasingly used directly as load-carrying support elements for large-size multiple laminated insulating vitrification.

A characteristic property of glass as a construction material is brittleness. The aim has therefore always been to avoid distortion and stress concentration wherever glass is incorporated into structures. There is a considerable risk of sudden cracking during erection – great care must be taken when the glass elements are installed.

Aims to be achieved with glass/concrete constructions:

- combining the advantages of glass and concrete
- compensation of the disadvantages of glass
- avoiding stress build-up by prestressing the glass
- skillful combining with other materials, in order to achieve ductile system-behaviour
- designing with an eye to glass special properties
- aesthetically pleasing design.

Anyway the glass elements are to be formed in such a way that even if they fail, some load-carrying capacity is left and the supporting structure still remains standing if a certain number of prefabricated glass elements fail.

As regards building support structures, one can in principle distinguish between applications involving plate elements, those involving panes and those involving rod (beam) elements. The load capacity of glass is exploited best if the glass element can work as wall-disk as well as a shear stress is available in glass-sheet. Disc-type elements include compression elements, shear fields and wall-type beams. Disc-type load capacity involves shear transmission via linear connections. One way of transmitting shear forces linearly is to mesh the surfaces to be connected by knurling them, and to fill the gap by injecting mortar (bridge in the BMW museum).

It is possibe to increase the load capacity of glass by prestressing, as with prestressed concrete. Prestressing locks up existing flaws, making the system element more rigid overall; as a result, narrower bottom flanges suffice to take advantage of the prestressed steel cross-section.

2. CONNECTIONS BETWEEN GLASS AND STEEL – STATE OF THE ART

Depeninding on how forces are transmitted, the following (more complex) systems arise [1]:

2.1. Form-locked (positive) fastenings (bolts and bearing connections)

In steel construction, one can start from the elastic-plastic behaviour of steel, simplifying from a uniform distribution bearing stress, since local stress peaks relocate themselves through local plasticity. This is also possible with glass but very much restricted. So a sleeve (made of aluminium, plastic, teflon, polyamide, epoxy, polyester or polyurethane) is inserted between a bolt and the glass bore to reduce stress peaks and disperse the bearing stress on the glass as uniformly as possible. Depending on the tolerances in the bore zone, the load may be distributed unevenly [2].

Basically two types of sleeve are possible [3]:
- prefabricated (precast) sleeves
- sleeves cast on site.

Prefabricated sleeves are easy to assemble on site, but require close tolerances. This is a disadvantage with multiple bolt connections, for example.

Sleeves cast on site are trickier to assemble because they need grouting with resin. The glass pane must be held up for the resin to harden in the right position. Sleeves cast on site allow larger tolerances, which is an advantage with laminated glass. A connection of this kind is calculated rather as for such connections in steel structures. The mechanical properties of the sleeve material must be provided by the manufacturer.

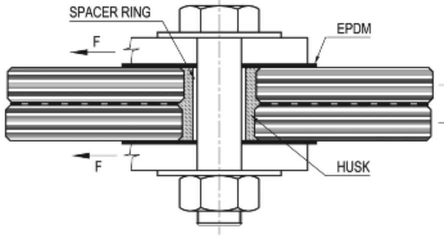


Figure 1.
Bearing connections (fastenings)

Linear and punctual chump also belongs to the category of fastenings with positive locking. The panes are fixed in place in a framework with glasswork spacers (if necessary in conjunction with chunk-bridges). The spacers must have uniform support if they are to function properly over long periods.

2.2. Force-locked joints (frictional and contact connections)

Friction-grip connections (fastenings) have the advantage of gradual load introduction and can therefore take on higher loads than bearing connections. Forces can be transmitted via friction by the mechanical denticulation of the micro-roughness of both contact surfaces. Alongside the mechanical denticulation adhesive forces also appear. It is standard practice to use prestressed bolts (as in steel construction: high-strength friction grip fastening) to activate the friction force [4]. The elasticity and fatigue strength of the intermediate layer make a big difference to the quality of the friction connection. Soft metals (pure aluminium), fibre-reinforced plastics such as KlingerSil or materials like cork, leather or cardboard can be used for this. KlingerSil is a high-pressure sealant with a friction coefficient of approximately 0.1 to 0.15. A key requirement is that these materials always remain elastic, with low creepage deformation and low settling, that are essential to withstand the prestressing force. The friction coefficient is declared by the manufacturer or is determined in tests.

Causes of frictional connection failure:

- the contact surfaces slip because of changes in the friction qualities (moisture penetrates).
- slip because of diminishing clamp force (for example creepage appearance, appearance of external tension forces).
- glass-break through to high prestressing with, to yield, to stiff or also geometrically unfavorably moulded clamping plates.

The problems with friction connection are the unevenness of tempered glass and the fact that laminated toughened glass cannot be used [4], since the prestressing effects dwindle away through creep of the polyvinyl butyral foils (PVB).

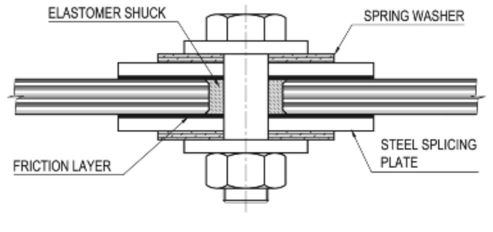


Figure 2.
Frictional connection

Contact connections can transmit only compressive forces which appear perpendicular to the contact surface. External tension forces can be to take up to a decompression over the contact surface, prestressed on compression. To avoid excessively high stresses in the area where the force is applied, the contact surfaces must be large enough. In the case of hard materials, as with contact glass-glass or glass-steel, an elastic intermediate layer becomes necessary. This is also to be borne in mind so that possible geometrical inaccuracies can be absorbed. The load can be transmitted at different points. The primary question is therefore how is the load on the glass pane aligned [5]:

- normally to the glass pane
- in the plane of the glass pane.

A contact connection fails if the contact surfaces are displaced relative to each other by agitation, rupture or major deformation. This is possible if, say, a bent glass-plate slips from the retaining band (clamp batten). The contact materials must bear its compression load up.

2.3. Positive substance joining (splicing) (adhesive bond)

Adhesive bonding for glass components is widespread in the construction industry. It always involves relatively large contact surfaces and the use of elastic adhesives.

Adhesive bonding provides virtually uniform load introduction [3]. The behaviour of the connection can be adjusted by modifying the properties and thickness of the adhesive.

Thin adhesive layers result in stiff connections with higher stresses at the ends of adhesive layers. Thick adhesive layers suffer greater distortion.

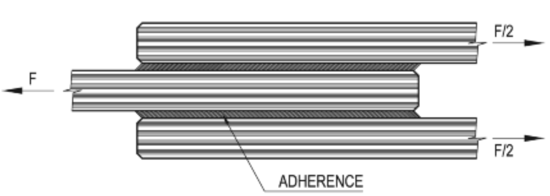


Figure 3.
Adhesive connection

The forces to be transmitted are usually very small. How much force adhesive connections can transmit clearly depends on environmental influences such as temperature, UV radiation and moisture, on how long the load is applied, and also on the geometry of the adhesive joint. In the case of a fire the connection normally fails.

3. CONTINUOUS BOND BETWEEN GLASS AND STEEL BY MEANS OF UHPC

With the glass construction glass elements (in general glass panes) are joined to the supporting structure by mechanical connection means (screws, bolts, dowels) or by bonding together. The problems with this type of construction method are obvious, given the load-bearing characteristics of the building material glass itself: Glass is brittle and its tensile strength is only a fraction of its compressive strength.

With point, the high shear strength of glass panes cannot be exploited to the full. This paper shows a new approach in which a linear continuous bond is made between glass and steel. The load is the edges. With this system the composite stresses are transmitted not directly from the glass into the steel, but indirectly via a grouting medium.

3.1. State of the technology

Concrete structures can be joined to glass elements along an edge very simply, in that the glasswork is encased directly with fresh concrete and remains in thereby emerging groove (slot). The glass surface is either roughened beforehand or else conveniently (in the suitable line) coated. The bond between glass and concrete is effected mainly by meshing, but also by friction, and involves a complex interplay of the following processes:

– concrete shrinkage
– development of the concrete tensile and compressive strength
– development of the concrete elastic properties
– concrete creep due to stresses produced by constraints.

The force normal to the contact surface needed for frictional connections results from shrinkage of the concrete. How much shear force can be taken up then depends only on the state of the glass surface. The surface roughness of the glass edges can be ensured by matt finishing (sandblasting, acid treatment) and coating procedures (enamelling).

The interface between glass and concrete is called a shear joint, because the transmittable shear tension there influences the increase in load capacity. To transmit shear tension, the shear joints between glass and concrete are in this case implanted without reinforcement. Glass can take up very high stresses in direct pressure contact with concrete, provided that the contact surfaces fit together exactly.

The main focus of this work lies in the examination of frictional connections which can transmit the forces diagrammed in Figure 4 [6]. It is also possible to connect a glass pane without pre-treatment; in this case, though, only compression forces ny and bending moments mx can be transmitted, which limits the possible applications.

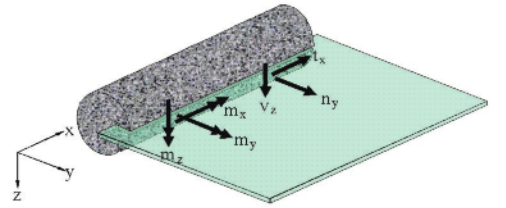


Figure 4.
Transmittable loads (possible transmission of forces)

3.1.1. Systems with UHPC

For the glass pane and concrete elements to work together, an intact bond is necessary.

- **Tensile strength**

The bond load-capacity is restricted by the tensile strength of the concrete close to the surface. This is why only ultra high-strength concrete is used here [6]. The tensile strength of UHPFRC is a function of (a) the tensile strength of the cement matrix, and (b) the contribution of the steel fibres in the UHPFRC.

- **Shrinkage constraints**

While the concrete is shrinking, the glass is exposed to compressive stress, provided that the resulting internal stress is not dissipated by cracking or tensile creepage of the concrete. This internal stress is actually desired for a better clamping effect in the connection zone. The concrete undergoes tensile stress and cracking to the same extent. Glass is a very stiff material and does not yield as the concrete shrinks, so that glass can cause cracking even in a high-strength fibre-reinforced concrete [6].

- **Creeping redistribution (relocation)**

Since glass is not subject to creeping deformation, only stress transmission from concrete to glass is an issue.

3.1.2. Bonding with mortar-type materials

In 2007, as part of the rebuilding of the BMW museum in Munich, a footbridge with a span length of 16 m was planned and implemented as a glass-steel structure. The BMW bridge in Munich is an interesting example of application-from the point of view of building practice and manufacture. The side walls of the bridge serve as main girders. The side walls are designed with a top and bottom flanges in steel and laminated sheet glass (LSG) as infill.

In order to transmit the shear forces involved into the glass panes, the edges of these plates are given a special cut and the surface of the steel components is corrugated. The space between is filled with a two-component mortar (Hit HY 50, manufactured by Hilti). By way of prestressing and meshing the materials, the shear force should be transmitted through the joint, which needs to be approximately 5 mm across. The following illustration shows the planned implementation.

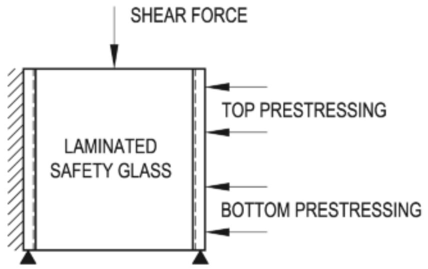


Figure 5.
Notches in glass and steel

The company BMW Group Mobile Tradition, Munich, commissioned the laboratory for steel and aluminium construction at Munich Engineering College (Fachhochschule) to perform basic testing of the load capacity of the shear connection. The tests showed that the load capacity of the shear connection essentially depends on the form of the cut on the pane edge. As it turned out, every single test specimen failed because the mortar fractured.

The test specimens were installed in a test rig in which pressure could be applied to on the flats via 4 threaded rods to simulate prestressing. The specimens were supported on the flat on one side; on the other side they could be loaded in the plane of the pane by means of a hydraulic cylinder (see Fig. 6).

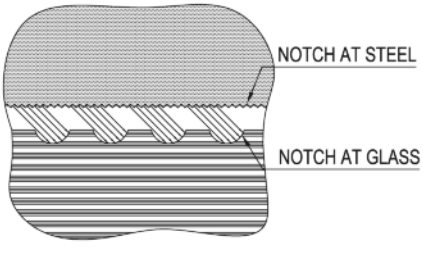


Figure 6.
Scheme of test arrangement

The test specimens were loaded statically and were prestressed to a greater or lesser extent:

- Specimens 01 / loaded statically with low prestressing
  The prestressing was adjusted to approximately 2 x 15 kN. Subsequently the specimen was loaded up to failure. The load was increased gradually, and the specimen was repeatedly relieved of the load.
  Both joints failed at a maximum load of 207.8 kN. The grouting compound failed on shear. The prestressing force increased from a shear force of approximately 120 kN on.
- Specimens 02 / loaded statically with high prestressing
  The prestressing was adjusted to approximately 2 x 30 kN. Subsequently the specimen was loaded up to failure. The load was increased gradually and the specimen was repeatedly relieved of the load.
  Both joints failed at a maximum load of 248.4 kN. The grouting compound failed on shear. The prestressing force increased from a shear force of approximately 200 kN over 2 x 30 kN. The pane fractured only after failure, when it hit the test frame.

All specimens failed at loads which lay over a theoretical shear angle of 45°.

3.2. Experimental investigations

The aim of the program is to construct a glass composite structure in which panes of glass are clamped in steel-concrete frames as load-bearing elements. The main problem is the quality of the bond between the load-bearing glass elements and load-bearing steel elements in the composite structure with the aid of ultra–high-strength concrete. The main question would be what the shear strength of the bond is. To answer this question, laboratory tests and computer-assisted calculations must be conducted in parallel.

Fabricating the connection by means of saw-teeth, waves etc. was ruled out here for economic reasons.

According to the thesis by Freytag [6], further investigations may now make it possible to define how to dimension glass/concrete composite structures in future. The results of computer simulation and the results of the laboratory tests should be largely identical.

An experimental method for determining the strength of the bond between glass and concrete was worked out in [6] and developed further by the authors. As a result of the tests numerical values (maximum shear stress and shear flow) were compiled for the glass/concrete bond. In the future the formulae that relate bond strength to various parameters should be derived from evaluated tests. These values should be converted for panes of differing size and thickness by means of coefficients. These formulae should provide a basis for dimensioning of the composite structures.

Certain questions need to be answered here beforehand:

- What influence could the length and depth of the bond and the thickness of the glass have on the results of the tests?
- How large are the local disturbances in stress distribution in the region of load application?
- How is the stress distributed (tension curve)?
- What factors determine the strength of the bond between glass, UHPC and steel section?
- Could the meanstress level / shear flow be evidence of the strength of the bond?
- Which other variables could be used to describe the strength of the bond?
- Which of the values obtained can be used further for dimensioning glass-concrete composite structures?

3.2.1. Test and instrumentation set-up

Shear tests were carried out on glass composite specimens. The glass-concrete-steel composite test was performed with 36 specimens. The individual tests proceeded in 12 series of 3 tests each chronologically.

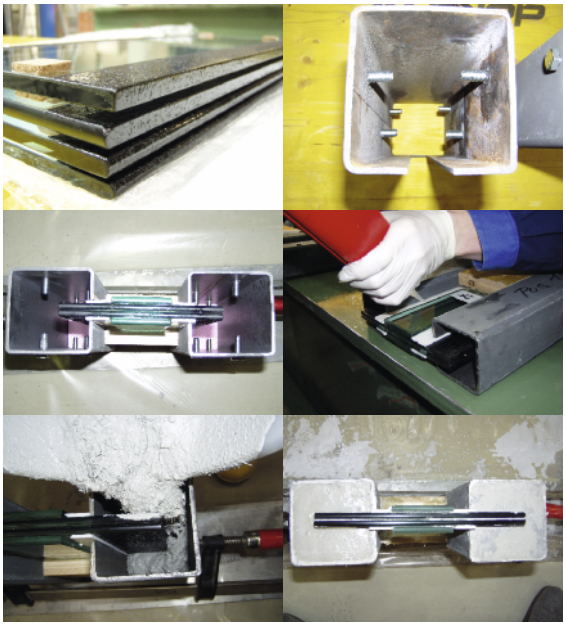


Figure 7.
Step-by-step fabrication of test specimens

The test specimens consist of glass panes and steel components. As previously mentioned, the edges of the panes are pretreated so as to obtain a positive bond between glass and concrete. The connection between glass edge and steel element is executed by filling the gap between with high-strength concrete. This way the glass edge is encased in concrete).

The following materials were used in manufacturing process: laminated glass bonded from thermal-hardened single sheets of safety glass (+ unhardened float glass to provide more strength at loading points), garnet sand (grain size 100), enamel lacquer (black), hollow steel sections (grade S235), screws M8 and M10 (strength class 8.8), UHPFRC ceracem made by Sika with steel fibres (fibre content 2% by volume), UV-hardened acrylic adhesive Delo-Photobond 4468 to bond glass sheets together.

Figure 8.
Materials used: glass, concrete, hollow steel sections, UV-hardened adhesive

A pressure/pressure/shear body was used for the tests.

Figure 9 should clarify the test set-up. A steel rail with a trapezoidal groove was bonded to the face of the glass body visible in the plan with Sikadur 31 CF Normal solvent-free moisture-proof thixtropic two-component adhesive. This rail was then loaded by means of a hydraulic press via a loading roll. The loading roll is hinge-connected with the test cylinder. The glass pane was pressed downward from above and was loaded until the specimens failed. The test is path-controlled with a constant piston speed of 1x10^{-3} mm/second. The gauges were attached symmetrically at both ends of the loading roll and on the specimens.

Data measured:

- force (MTS, KMD 1000 kN)
- piston travel (MTS, LVDT 250 mm)
- loading roll travel (symmetrically left and right)

(HBM; inductive travel sensor ±10 mm measured displacement, WA20)
- reciprocal displacement between concrete and steel components (diagonally left behind and right front) (HBM; elongation travel sensor ±2.5 mm measured displacement, DD1)
- reciprocal displacement between glass and steel components (symmetrically in front and behind) (HBM; inductive travel sensor ±10 mm measured displacement, W5TK).

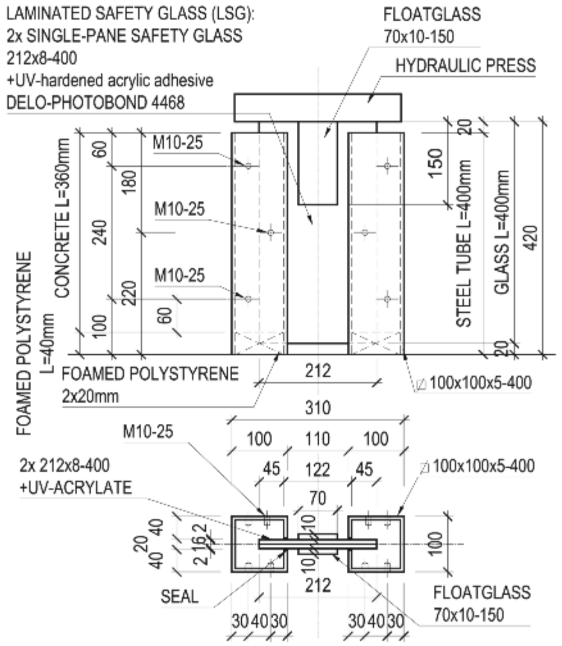


Figure 9.
Test set-up – series 100/45/16; dimensions in [mm]

The next illustration (Fig. 10) shows the arrangement of measuring points on the test specimens with the duplicate – and one's hips test bodies there.

3.2.2. Types of test specimen

The bond between glass and concrete was tried out on 3 types of specimen with different cross-sections. The range of variation:
- three glass sheet thicknesses: 2x6, 2x8, 2x10 mm
- three bond (grip) depths: 30, 45, 60 mm and
- three steel tube cross-sections: 100x100, 80x80, 60x60 mm.

Specimens without bolts to connect steel and concrete (OV – without bond) were also produced. To test another possible (advantageous) way of bonding materials together in future, one-sided specimens were also produced (S). Table 1 lists all types of specimen tested.

Figure 10.
Measuring set-up for symmetrical and one-sided tests

Figure 11.
Types of specimen tested

Table 1.
Overview of specimens tested

test no.	designation	maximum force [kN]	bolts	glass thickness [mm]	dimensions ESG	quantum	fixing in depth mm	failure type
GBSV 01	100/45/12	211.89	M10	6	212x400	2	45	GBV
GBSV 02	100/45/12	240.02	M10	6	212x400	2	45	GBV
GBSV 03	100/45/12	205.08	M10	6	212x400	2	45	GBV
GBSV 04	100/45/16	242.89	M10	8	212x400	2	45	GBV
GBSV 05	100/45/16	170.06	M10	8	212x400	2	45	GBV
GBSV 06	100/45/16	261.86	M10	8	212x400	2	45	GBV
GBSV 07	100/45/20	149.64	M10	10	212x400	2	45	GBV
GBSV 08	100/45/20	215.53	M10	10	212x400	2	45	GBV
GBSV 09	100/45/20	180.09	M10	10	212x400	2	45	GBV
GBSV 10	100/30/16	230.43	M10	8	182x400	2	30	GBV
GBSV 11	100/30/16	236.29	M10	8	182x400	2	30	GBV
GVSV 12	100/30/16	188.89	M10	8	182x400	2	30	GBV+ glass fracture
GBSV 13	100/60/16	186.10	M10	8	242x400	2	60	GBV
GBSV 14	100/60/16	158.81	M10	8	242x400	2	60	GBV
GBSV 15	100/60/16	198.39	M10	8	242x400	2	60	GBV
GBSV 16	80/45/16	130.14	M8	8	212x400	2	45	GBV
GBSV 17	80/45/16	131.55	M8	8	212x400	2	45	GBV
GBSV 18	80/45/16	175.30	M8	8	212x400	2	45	GBV
GBSV 19	60/30/16 OV	75.45	-	8	182x400	2	30	BSV
GBSV 20	60/30/16 OV	70.16	-	8	182x400	2	30	BSV
GBSV 21	60/30/16 OV	100.84	-	8	182x400	2	30	BSV
GBSV 22	100/60/1 6 OV	47.44	-	8	242x400	2	60	BSV
GBSV 23	100/60/1 6 OV	31.64	-	8	242x400	2	60	BSV
GBSV 24	100/60/1 6 OV	34.45	-	8	242x400	2	60	BSV
GBSV 25	80/45/16 OV	76.03	-	8	212x400	2	45	BSV
GBSV 26	80/45/16 OV	107.97	-	8	212x400	2	45	BSV+GBV
GBSV 27	80/45/16 OV	110.20	-	8	212x400	2	45	BSV+GBV
GBSV 28	100/45/16 OV	82.47	-	8	212x400	2	45	BSV
GBSV 29	100/45/1 6 OV	38.14	-	8	212x400	2	45	BSV
GBSV 30	100/45/1 6 OV	74.20	-	8	212x400	2	45	BSV
GBSV 31	100/45/16 S	113.43	-	8	75x400	2	45	GBV
GBSV 32	100/45/16 S	81.34	-	8	75x400	2	45	GBV
GBSV 33	100/45/16 S	80.62	-	8	75x400	2	45	GBV
GBSV 34	100/30/20 S	98.55	-	10	48x400	2	30	GBV
GBSV 35	100/30/20 S	96.04	-	10	48x400	2	30	GBV+ glass fracture
GBSV 36	100/30/20 S	130.51	-	10	48x400	2	30	GBV

Legend:
steel tube/bond depth/laminated glass thickness, e.g. 100/45/12 (12=2x6 mm); OV: without bond (screws); S: single (one's hips);
GBV: failure of glass-concrete bond; BSV: failure of concrete-steel bond

3.2.3. Results and interpretation

This section surveys the test results. All series were interpreted first in the end of experiments. These were divided into three groups for interpretation purpose:

- two-sided tests with bolts
- two-sided tests without bolts
- one-sided tests.

In almost all two-sided tests with bolts the failure occurred directly in the contact zone concrete-enamel (GBV). In one case the glass actually fractured.

In two-sided tests without bolts the failure occurred in the contact zone steel-concrete (BSV). In two cases the glass-concrete bond (right) and the steel-concrete bond (left) failed simultaneously.

In one-sided tests the glass fractured in one case. In all other cases, the drop in force was the consequence of the glass-concrete bond failure.

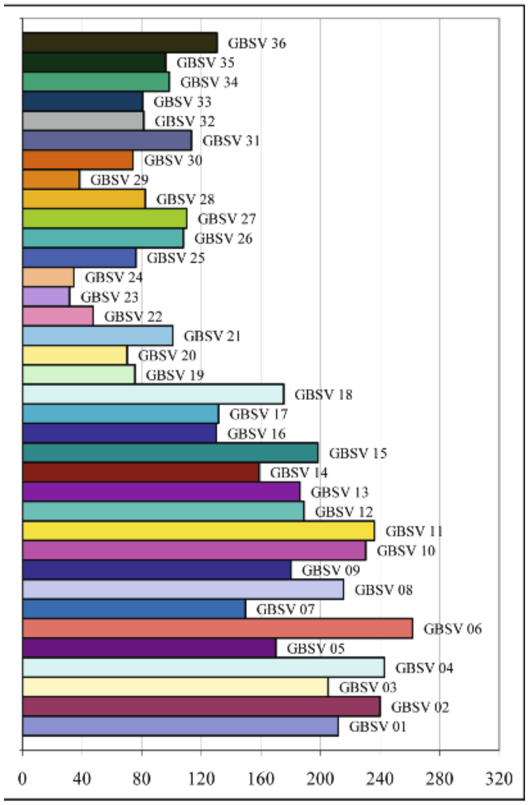


Figure 12.
Maximum force [kN] in tests GBSV 01 to GBSV 36

The following parameters are evaluated: forces and displacements. At first glance (sight), one can say that:

- without system-dowels breaks the steel/concrete bond fails before the glass/concrete bond does; with smaller tube cross-sections greater loads can be accomodated
- with dowels for composites greater loads can be accomodated with larger tube cross-sections (the larger volume of concrete results in greater clamping force (a function of concrete shrinkage)
- in one-sided tests the maximum load is achieved with the thicker panes
- variations in embedding depth have no influence on the results.

According to [6] the load capacity of the glass/concrete bond can bebroken down into several parts.

Before the load reaches the maximum, transmission of force depends on the quality of the contact surface (adherence bond and finish roughness) and on pane thickness (the clamping force). The dependence of the part load capacities on embedding geometry has not been examined to date. Based on the assumption that bond strength depends on the size of the contact surface (in our case, with length L=constant, on the depth of embedding and pane thickness), the results can be shown as mean bond shear stress at the contact surface (t=F/A), where F is the maximum load and A the surface area in contact with the concrete (after suitable preparation). This means: 2x flank + 1x front (in symmetrical tests 2x).

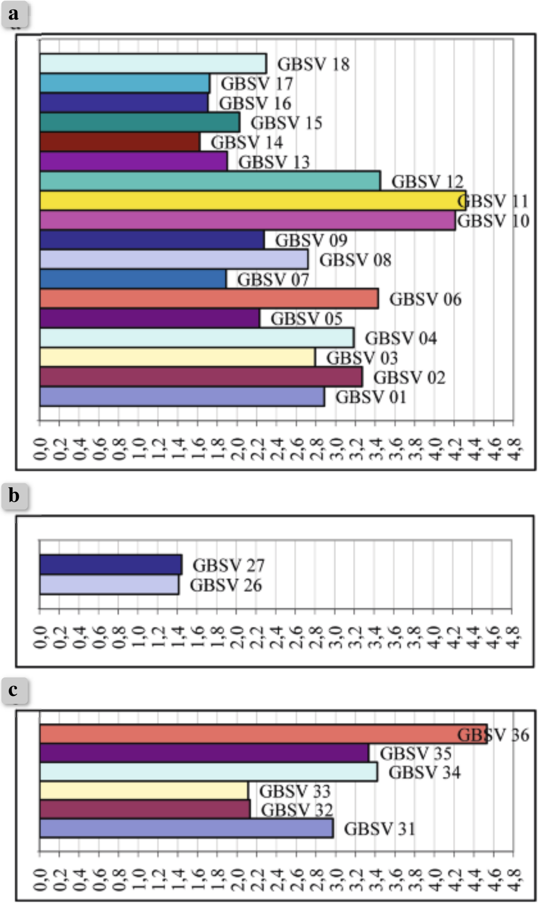


Figure 13.
Maximum bond shear stress [N/mm2]
a) with bond (screws); b) OV: without bond (screws);
c) S: single (one's hips)

Figure 13 is an overview of all results as bond shear stress (t=F/A), figure 14 is a corresponding overview in terms of bond shear flow (t=F/L).

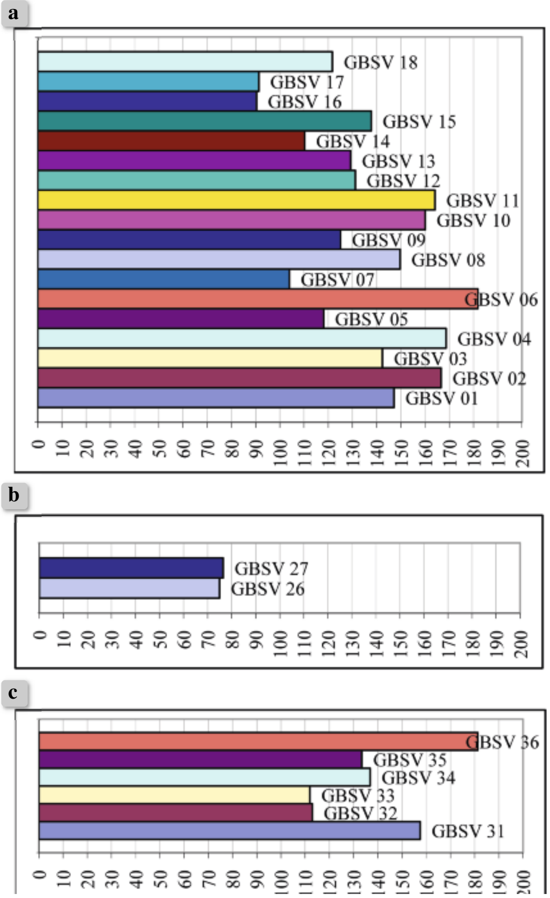
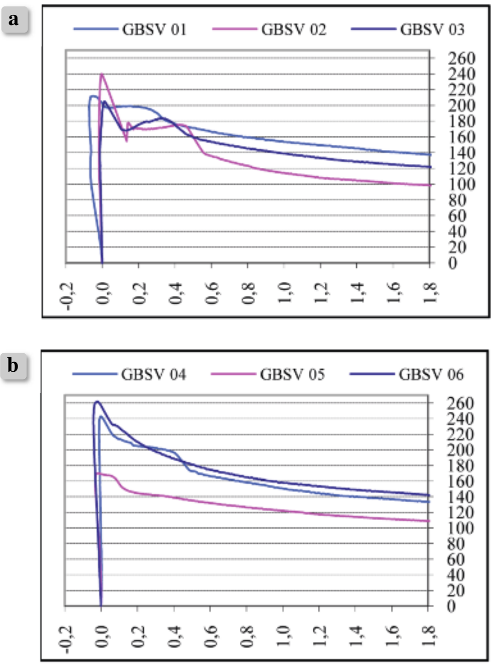
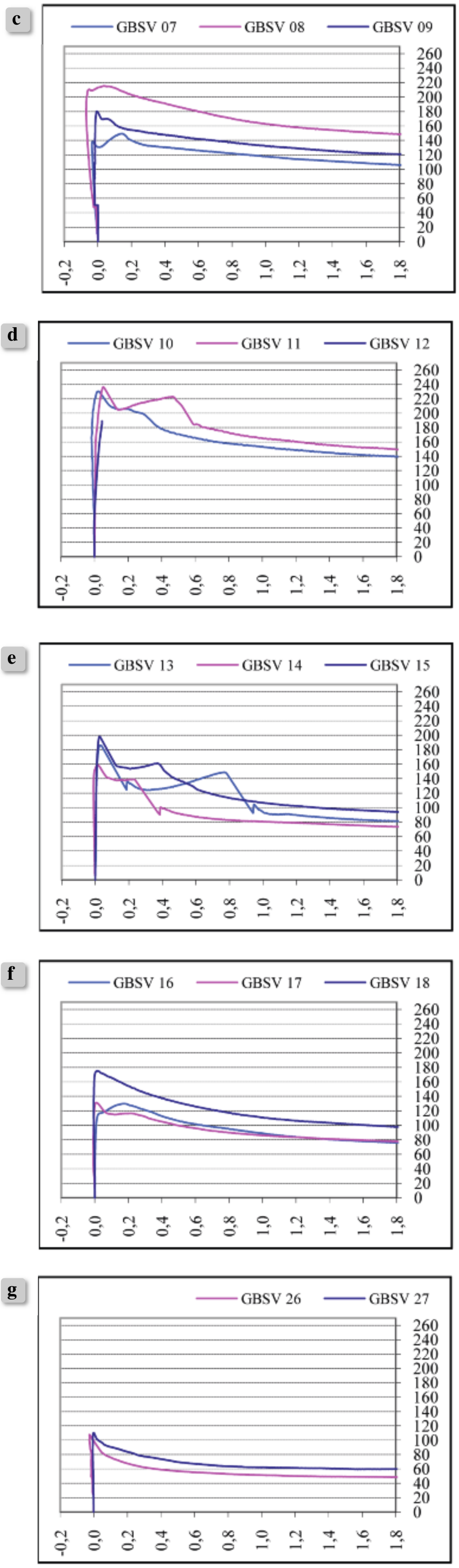


Figure 14.
Maximum shear flow [N/mm]
a) with bond (screws); b) OV: without bond (screws);
c) S: single (one's hips)





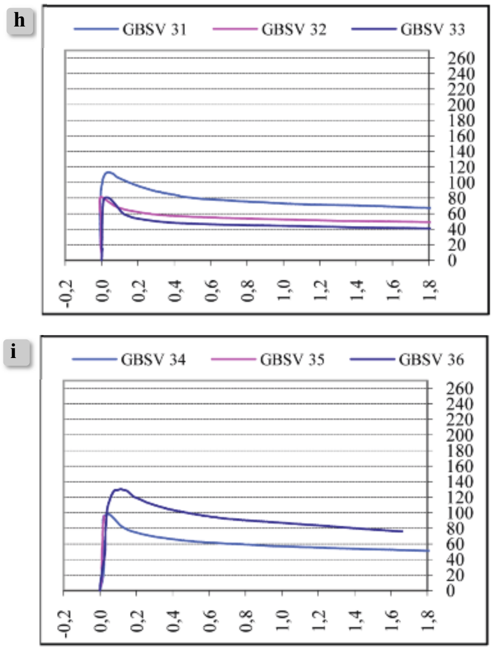


Figure 15.
Maximum force [kN] – displacement between glass and concrete [mm]
a) 100/45/12, b) 100/45/16, c) 100/45/20, d) 100/30/16, e) 100/60/16, f) 80/45/16, g) 80/45/16 OV, h) 100/45/16 S, i) 100/30/20 S

The diagrams below show the displacements between glass and concrete under load. During the tests only the displacement between steel and concrete "a" and between steel and glass "b" (the median value of the data from each side) were measured. The displacement between glass and concrete was calculated c=a-b as the difference between these data.

To interpret the results a start was made with the tests in which the drop in force was symmetrical (left-right). After the load reaches the maximum, two parallel curves on the left and right side in symmetrical tests confirm that the bond between glass and concrete failed simultaneously at similar speed on both sides of the specimen.

A comparison of the three series 100/45/12, 100/45/16, 100/45/20, with constant depths of embedding and with the same steel sections, but with differing pane thickness, does not confirm the supposition that the size of the clamping force is a function of pane thickness. The values of the maximum transmission load vary considerably. The best result is achieved with the medium pane thickness (table 2 contains exact values). The maximum force in one-sided tests with specimens of similar design to those in symmetrical tests, i.e. 100/45/16, amounts to 113.43 kN (GBSV 31); multiplying by 2 we get 226.86 kN, comparable with the maximum force of 261.86 kN in symmetrical tests.

A comparison of the three series 100/30/16, 100/45/16, 100/60/16 with constant pane thickness and with same steel sections, but with different depths of embedding does not confirm that bond strength varies in proportion to the bond depth .

There are still too few results on hand for us to be able to compare series with different steel cross-sections, such as 100/45/16 and 80/45/16. The tests with specimens fabricated without bolts which ended with the steel/concrete bond failing will be continued after concrete has been added at the bottom of the tubular sections (approx.1.5 cm concrete thickness).

The data are affected by several uncertainty factors that cannot be excluded. The following were also measured:

- specimen buckling
- fluctuations in the thickness of the adhesive layer between the glass and the rail introducing the load
- strains in the entire test set-up: supports, loaded edge.

Table 2.
Overview of results with respect to force [kN]

specimen	force	value [kN]	mean value in series of 3 specimens [kN]	test no.	designation
symmetrical with dowels	maximum minimum	261.86 130.14	224.94 145.66	4,5,6 16,17,18	100/45/16 80/45/16
	mean value		195.16		
symmetrical without dowels	maximum minimum	110.20 31.64	98.07 37.84	25,26,27 22,23,24	80/45/16 OV 100/60/1 6 OV
	mean value		70.75		
one-sided with dowels	maximum minimum	130.51 80.62	108.37 91.79	34,35,36 31,32,33	100/30/20 S 100/45/16 S
	mean value		100.08		

Table 3.
Overview of results with respect to shear stress [N/mm^2]

specimen	force	value [kN]	mean value in series of 3 specimens [kN]	test no.	designation
symmetrical with dowels	maximum minimum	4.32 1.62	3.99 1.85	10,11,12 13,14,15	100/30/16 100/60/16
	mean value		2.66		
symmetrical without dowels	maximum minimum	1.84 0.32	1.50 0.39	19,20,21 22,23,24	60/30/16 OV 100/60/1 6 OV
	mean value		1.01		
one-sided with dowels	maximum minimum	4.53 2.11	3.76 2.41	34,35,36 31,32,33	100/30/20 S 100/45/16 S
	mean value		139.00		

Table 4.
Overview of results with respect to shear flow [N/mm]

specimen	force	value [kN]	mean value in series of 3 specimens [kN]	test no.	designation
symmetrical with dowels	maximum minimum	181.85 90.37	156.21 101.15	10,11,12 16,17,18	100/30/16 80/45/16
	mean value		135.35		
symmetrical without dowels	maximum minimum	76.53 21.97	68.10 26.28	25,26,27 22,23,24	80/45/16 OV 100/60/1 6 OV
	mean value		49.13		
one-sided with dowels	maximum minimum	181.27 111.97	150.51 127.49	34,35,36 31,32,33	100/30/20 S 100/45/16 S
	mean value		139.00		

The glass/concrete/steel composite structures were tested with Ultra-High-Performance Fibre-Reinforced Concrete UHPFRC of the following variety: ceracem from Sika with steel fibres.

The tests discussed also involved concrete properties such as compressive strength, tensile strength and modulus of elasticity. The following test specimens were fabricated:

- 3x cubes 10 cm for testing compressive strength
- 2x prisms 12/12/36 cm for testing the relationship between tensile strength and elongation
- 6x prisms 4/4/16 cm for testing the modulus of elasticity.

The specimens were stored in a similar way to the composite specimens (storage in air).

Table 5 lists the results of compressive strength testing with the use of 10 cm cubes after 28 days. The mean compressive strength value was found to be 196.2 N/mm^2.

Table 6 presents the results of testing for modulus of elasticity with prisms 4/4/16 cm after 33 days. in addition to the secant modulus (E modulus 33) at approximately 33% of the anticipated stress at failure as per ÖNORM B 3303, the secant modulus (E modulus 70) was determined at approximately 70% of the stress at failure, as recommended by the University of Kassel for testing UHPC.

Table 5.
UHPFRC "ceracem" with steel fibres – compressive strength and gross density of concrete cubes with nominal dimension 10 cm (as per ÖNORM B 3303)

specimen no.	specimen age [d]	maximum force [kN]	compressive strength [N/mm^2]	deviation from mean value [%]	gross density [g/cm^3]
M2 Wl	28	1974.0	197.4	0.60	2.750
M2 W2	28	1946.7	194.7	-0.79	2.775
M2 W3	28	1963.8	196.6	0.18	2.751
mean value			196.2		2.759

Table 6.
UHPFRC "ceracem" with steel-fibres - Young's modulus examination at prisms 4/4/16 cm

specimen no.	specimen age[d]	stress at pre load σ_b [N/mm^2]	strain ε_b [‰]	stress at upper load σ_a [N/mm^2]	strain ε_a [‰]	stress at σ_{70} [N/mm^2]	strain ε_{70} [‰]	E modulus E_{33} [N/mm^2]	E modulus E_{70} [N/mm^2]
MP1	33	6.9	0.25	66.1	2.750	103.6	2.47	46614	43554
MP2	33	4.9	0.23	51.0	2.775	105.5	2.55	46170	43379
MP3	33	5.2	0.17	52.9	2.751	99.2	2.32	44962	43702
mean value					2.759			45915	43545

Table 7.
UHPFRC "ceracem" with steel fibres - associated testing for compressive strength with prisms 4/4/16 cm

specimen no.	specimen age [d]	load at failure [kN]	compressive strength [N/mm^2]	deviation from mean value [%]	gross density [g/cm^3]
MP1	33	236.0	146.0	0.07	2.711
MP2	33	242.0	149.8	2.61	2.688
MP3	33	226.1	142.0	-2.68	2.693
mean value			145.9		2.697

4. CONCLUSIONS AND OUTLOOK

The weak points of glass/concrete composite beams are the glass web and the bond between glass and concrete.

An evaluation of the tests of bonding effect between glass and concrete with various steel sections, depths of pane embedding and panes thicknesses reveals that:

- Simplified conversions between the maximum transmittable force, shear stress and shear flow in the joint between glass and concrete confirm that the distribution of the bond stress in the contact surface is linear neither in the embedding depth) nor longitudinally. The actual distribution will be identified in the next phase of investigation.
- The adhesive bond between steel and fresh concrete hinders concrete from shrinking - from which we can infer a diminished increase in the clamping force. Before the maximum load is reached, transmission of force largely depends on the clamping force. With thicker panes a greater clamping force can be anticipated – which does not apply here, though, because the concrete is prevented from shrinking.
- In Freytag's thesis [6] bonds achieve a strength of 6.8 N/mm^2 with UHPC 150 concrete and of 8.4 N/mm^2 with Ductal® white concrete where a corundum/enamel coating is applied. According to the thesis in question these are among the best results. In case of bond stress the best value was 4.5 N/mm^2, achieved with ceracem concrete .
- At this stage of evaluation it is not yet clear whether combining a corundum/enamel coating with ceracem concrete from Sika yielded better results than using Ductal® concrete. Here a detailed scientific study (thesis by author) is required, and is already in progress.
- The bond between open tubular steel section (the steel surface was carefully cleaned with a motor-cleaning agent before concreting) and set concrete achieves maximum value of approximately 1.3 N/mm^2.
- During two tests in the series 80/45/16 OV simultaneous failures occurred at the concrete/steel contact surface on the left side of the specimen and at the glass/concrete contact surface on the right side. Further tests will be needed to find out which cross-section geometries the load transmission can be greater for a steel/concrete bond without dowels than for a glass/concrete bond.
- With the test set-up in form of one-piece specimens there were problems in establishing the true position of the focus of the linear load from the test rig. The midpoint of the loading edge and of the steel rail bonded to the narrow side of the glass-front was halfway through the embedding depth. In the course of the test the rail turned to one side. This would not happen if the shear stresses were distributed linearly in the direction of embedding depth and inaccuracies in fabrication could be eliminated. The fact that the rail is not bonded in place symmetrically contributes to these inaccuracies.
- In order to decide whether the test set-up developed recently is suitable for further tests, the existing test data should be looked at and interpreted in more detail.
- The load can go on increasing after the first

appearance of cracking initiation in the glass, even if both panes are cracked.

- The bond formed by UV-hardened acrylic adhesive between the single panes is not stiff enough for the failure of one pane to lead to the failure of others.
- No cracks developed in the panes as a result of overloading at pane edges due to shear stresses.
- Pane failure was due to local flaws in the glass and/or local overloading at points where the load was applied.

For the test specimens fabricated to date tubular steel sections and panes of safety glass in three different thicknesses were employed. It would be worth conducting a series of tests with other glass thicknesses and types of section, yielding a different failure value and presumably a different pattern of destruction.

To model the failure mechanisms one must find out exactly how forces are distributed in the specimen, especially in the area of bond joint. Once the displacement and strain data have been evaluated, the failure mechanism can be described and inferences drawn about composite behaviour. The results are then used for numerical simulation with a finite-element volume model. For comparison the displacements and strains are recalculated variably, taking an perfectly elastic and non-linear material behaviour as a basis.

The aim of elaborating the test models by means of the finite-element method was to determine behaviour of glass/concrete contact surface under critical forces. Numerical analysis proved to be a very helpful tool, leading to successful evaluation of global strains and local stresses in glass.

The observations mentioned above from the tests just concluded raise basic issues which are to be dealed with first. Obviously the range of problems is very wide. Furthermore, it appears important to develop simple, objective and reproducible procedures with which the factors of significance for bond can be quantified with sufficient accuracy in practice. Future work will be concerned with investigating experimentally how the shear stress behaves over the bond length as an alteration of the normal force in the glass/concrete composite. The results should ultimately contribute to improving quality (and maximum load capacity at the same time) and to shortening the amount of time needed for designing glass composite structures with ultra–high-strength concrete.

In planning tests with fabricated elements, one must not neglect the basic material investigations, which are absolutely essential for correct design – particularly bond effect between glass and concrete.

The new trends in the construction industry, such as the glass/concrete/steel composite structures mentioned here, open up a wide spectrum of design options which awaits elaboration and practical application.

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