Scientific report – Host report

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Introduction

A 'classic' closed-cavity façade unit consists of an outer single glass layer, an inner insulating glass unit and a fully sealed cavity in between, as depicted in Figure 1. This cavity is pressurized with dry air to prevent condensation and to minimise cleaning operations. Reducing the cavity width potentially is of tremendous economic importance, as it would maximise the net usable floor area for a given building volume. To structurally enable the proper performance of such façade units, the use of cold-formed steel is investigated as it is stiffer and stronger than commonly used aluminium. Moreover, the coefficient of thermal expansion of steel lies significantly closer to the one of glass than the one of aluminium does. Revolutionary adhesive connections can therefore be developed, leading to an increased involvement of the glass as a load-bearing material in the overall structural behaviour of the unit. This is the main focus of the visitor's PhD. As comfort and energy efficiency issues are of major importance, the thermal performance is investigated as well. Possible solutions to mitigate thermal bridges to minimise heat loss and to improve thermal inertia to conserve energy are developed. Eventually, a good compromise between embodied energy and operational energy in terms of increasing energy efficiency leading to an optimisation of resources is strived for. The hosting partner has major expertise in this field, particularly applied to cold-formed steel wall systems. In the end, the innovative result should be a structural closed-cavity façade (SCCF) unit complying with the most strict environmental standards and guidelines.

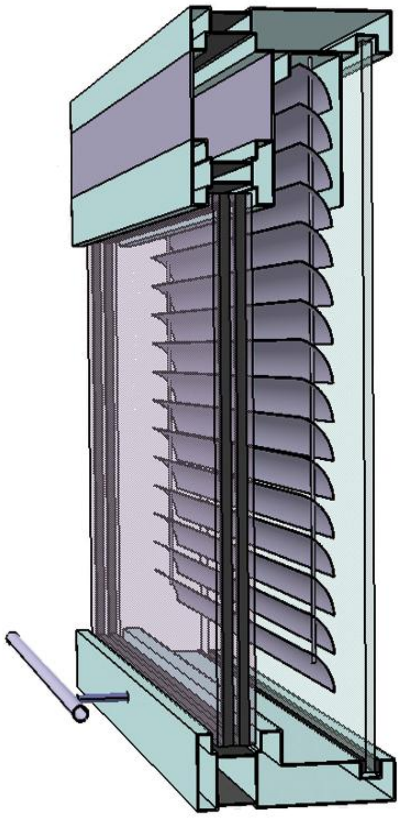


Figure 1: Closed-cavity façade unit (© Gartner)

The main aim of this Short-Term Scientific Mission (STSM) was to develop a holistic concept by sharing highly complementary knowledge of both participating institutions. At the Institute for Sustainability and Innovation in Structural Engineering (ISISE) at the University of Coimbra, knowledge regarding thermal behaviour and energy efficiency of lightweight steel-framed structures is available, which is invaluable in the development of a structural closed-cavity façade unit, specifically to comply to energy requirements imposed by decision-making bodies. The expertise of the Laboratory for Research on Structural Models (LMO) at Ghent University regarding hybrid cold-formed steel-glass façade units and structural adhesive connections is valuable to develop new lightweight steel-framed construction systems investigated at ISISE.

Description of the work

Outline

During the period of this Short-Term Scientific Mission, preliminary research on the thermal behaviour of a basic functioning structural body of structural closed-cavity façade was performed by means of experimental tests and two-dimensional numerical modelling. The basic functioning structural body or the skeleton consists of a cold-formed steel frame onto which a glass panel is adhesively attached on each side. Using finite element software, the effect of several parameters, such as cavity width, section type, section thickness, etc., on the thermal performance of the basic unit was investigated. Afterwards, possible techniques to mitigate thermal bridges and to limit the thermal transmittance of the unit were discussed and assessed. This, and possible solutions to connect several units which were designed, will feed the follow-up investigation which is planned after this Short-Term Scientific Mission.

Thermal transmittance

The thermal transmittance or U-value is a generally accepted quantity to assess the thermal performance of building elements and to impose thermal requirements by decision-making bodies. The thermal transmittance or the U-value of a hybrid cold-formed steel-glass façade unit can be defined as the parameter which characterises the heat transfer through this unit. It states the steady-state density of heat transfer rate per temperature difference between the environmental temperatures on each side (NBN 2008a; NBN 2011). The units of the U-value are W/(m²K). This parameter is used to measure how effective façade units are at preventing heat from transmitting between the inside and the outside of the building. Within the framework of the European Energy Performance of Buildings Directive (EU 2002) of 22 December 2002, the Flemish government imposed the following maximum U-values for curtain walling, corresponding to NBN EN 13947 (NBN 2007), as of January 2016:

$U_{cw,max}$ = 2.00 W/(m²K)
$U_{g,max}$ = 1.10 W/(m²K)

where $U_{cw,max}$ = the maximum overall thermal transmittance of the curtain wall element
$U_{g,max}$ = the maximum thermal transmittance of the glazing

Hence, when a hybrid cold-formed steel-glass façade element is mechanically fully developed, it has to be ensured that the thermal performance complies to the imposed requirements, i.e. the aforementioned U-values. If not so, measures have to be taken to guarantee a proper thermal performance. Of course, these applied techniques in turn will affect the mechanical behaviour. Hence, interaction between the thermal and mechanical behaviour such façade elements exists. Therefore, the development of a hybrid cold-formed steel-glass façade unit is an iterative process in which the consequences of measures to enhance the mechanical behaviour on the thermal behaviour have to be investigated and vice versa.

Experimental research

In a first step, the thermal properties of the structural adhesive, i.e. Sikasil® SG-500, were determined by small-scale experiments. By using Hot Disk TPS 2500 S equipment, as depicted in Figure 2, thermal conductivity λ, specific heat capacity c and thermal diffusivity α of the silicone could be determined in accordance with ISO 22007-2 (ISO 2008). Therefore, a Hot Disk Sensor with a radius of 6 mm was placed in between two 34 mm x 20 mm x 12 mm (3 layers of 4 mm) beam-shaped specimens, as illustrated in Figure 3. The input parameters used during the tests were a heat power of 50 mW, a measuring time of 80 s and an interval of 30 min between consecutive measurements. Nine measurements were performed to determine the aforementioned thermal characteristics of the Sikasil® SG-500. The results are summarised in Table 1.

Figure 2: Hot Disk TPS 2500 S (© Hot Disk AB)

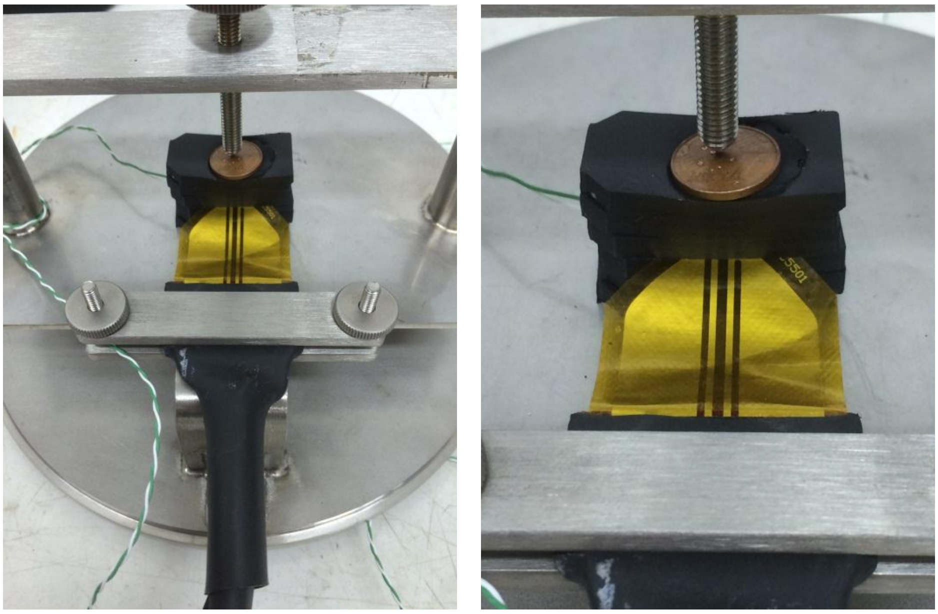


Figure 3: Experimental test setup

Table 1: Thermal properties of Sikasil SG®-500 determined according to ISO 22007-2 (ISO 2008) using Hot Disk TPS 2500 S equipment.

Test	Thermal conductivity	Thermal diffusivity	Specific heat capacity
	λ	**c**	**α**
	W/(mK)	mm²/s	MJ/(m³K)
1	0.3465	0.1790	19.354
2	0.3470	0.1794	19.337
3	0.3471	0.1796	19.326
4	0.3464	0.1785	19.409
5	0.3476	0.1800	19.317
6	0.3476	0.1800	19.317
7	0.3455	0.1769	19.532
8	0.3460	0.1778	19.455
9	0.3461	0.1779	19.460
μ	0.3466	0.1788	19.390
σ	0.00073	0.00109	0.0779
COV	0.21%	0.61%	0.40%

The measurements resulted in a thermal conductivity λ of 0.3466±0.00073 W/(mK) for the structural silicone Sikasil® SG-500. This value is comparable to the value of 0.35 W/(mK) for structural silicones, which is proposed by the standard NBN B62-002 (NBN 2008a) concerning the thermal performance of buildings. However, the manufacturer provides designers with a value of 0.25 W/(mK) for the Sikasil® SG-500 (Sika 2008), which is 28.6% lower than the measured value. Sikasil® SG-500 is a two-component structural silicone with a volume mixing ratio of component A (base compound) to component B (catalyst) of 10:1 (Sika 2015), which was used to produce the specimens from this research. A possible explanation is that the manufacturer used a different mixing ratio. Further, the manufacturer determined the thermal conductivity according to DIN 52 612 (DIN 1979) and not ISO 22007-2 (ISO 2008), although this cannot explain this large difference. Another possibility is that due to the fact that the specimens exist of three layers of 4 mm on each side of the sensor, very thin layers of air in between cause a loss of energy input. Therefore, additional tests will be conducted on homogeneous specimens with sufficient thickness to eliminate the latter effect. Furthermore, tests according to DIN 52 612 (DIN 1979) as used by the manufacturer will enable a comparison between both methods to determine the thermal conductivity of the structural silicone.

Numerical research

The measured value of the thermal conductivity of the Sikasil® SG-500 was implemented in the two-dimensional finite element software THERM (THERM 2015) to evaluate the thermal performance of a basic functioning structural body or the skeleton. The reference unit consisted of a 2.4 m x 2.4 m cold-formed steel frame using C100x2-sections. These sections are characterised by a web height of 100 mm, a flange width of 50 mm, a lip length of 12 mm and a thickness of 2 mm. Onto the basic frame, a 12 mm thick monolithic annealed glass pane is adhesively attached on each side. The adhesive joint, using Sikasil® SG-500 is 6 mm thick and is equally wide as the flange of the cold-formed steel section. The horizontal section of the reference unit is depicted in Figure 4.

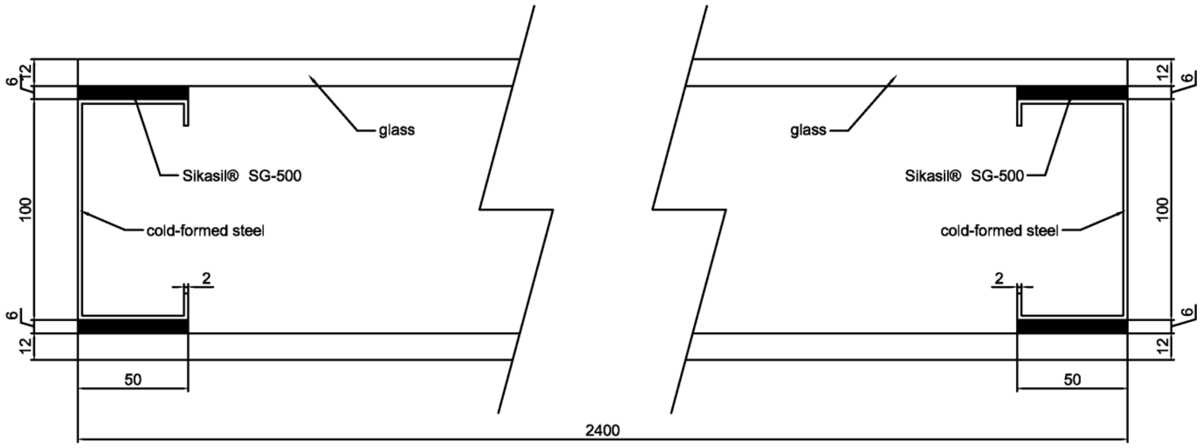


Figure 4: Horizontal section of a reference unit

The values of the thermal conductivities of the different materials used in the models are summarised in Table 2. Other input parameters are an interior temperature of 30 °C and an exterior temperature of 0 °C. According to ISO 6946 (ISO 2007) the interior heat transfer coefficient h_i can be equated to 7.69 W/(m²K) and the outdoor heat transfer coefficient h_e to 25 W/(m²K) for horizontal heat flow.

Table 2: Thermal conductivities implemented in THERM

Material	Thermal conductivity λ	Reference
	W/(mK)	
Sikasil® SG-500	0.347	Measured value
Quartz glass	1.400	NBN EN ISO 10456 (2008b)
Air[1]	Depends on cavity width	NBN EN ISO 6946 (2008c)
Steel	50.000	NBN EN ISO 10456 (2008b)

[1] Solid equivalent thermal conductivity.

With the aforementioned assumptions, a U-value of 2.78 W/(m²K) is obtained for the reference model, which is depicted in Figure 4. When only considering the U-value in the area of the steel frame, a value of 3.77 W/(m²K) was obtained, whilst the U-value for the area of the glass equalled 2.72 W/(m²K). As the U-value of the entire unit approximated the U-value of the glass, a limited effect of variations in the thermal transmittance of the frame on the global U-value was expected. This hypothesis was investigated by performing additional simulations in which the type of cold-formed steel section (open versus closed), the web height of the cold-formed steel section and the thickness of the cold-formed steel section varied. The results of these simulations are summarised in Table 3, Table 4 and Table 5.

The thermal transmittance of hybrid cold-formed steel-glass façade unit increases only with 0.98% when the frame is built up from tubular cold-formed steel sections instead of open C-sections with the same thickness. Increasing the thickness of the cold-formed steel tubular sections from 2 mm to 5 mm increases the U-value with 1.62%. Hence adding more steel to the frame (x2.4 from 2 mm to 5 mm thickness) has only limited effect on the global U-value of the unit, confirming the hypothesis of that the glass is the major contributor to the overall thermal performance of the hybrid cold-formed steel-glass façade unit. Increasing the cavity width of the unit by increasing the web height of the sections does not result in a significant decrease of the U-value.

When the width of the unit is decreased, it is expected that its thermal transmittance will increase. The contribution of the U-value of the frame (3.77 W/(m²K)) consisting of open C-sections to the overall U-value of the unit will increase, whilst the contribution of the thermal transmittance of the glass (2.72 W/(m²K)) will decrease. This effect was taken into account in simulations in which a cavity width of 1.2 m and 0.6 m were compared to the reference cavity width of 2.4 m. From the results, which are presented in Table 4, indeed an increase in the U-value for a decreasing unit width was derived. Decreasing the width of the hybrid façade unit from 2.4 m to 1.2 m led to a significantly smaller increase in U-value (+2.0 % for C-sections and +3.0% for tubular sections), than when the width is decreased from 1.2 m to 0.6 m (+3.9% for C-sections and +5.7% for tubular sections). Consequently, there is a value for the width of the unit for which an additional increase does not decrease the overall thermal transmittance of the unit significantly anymore. This implies that the contribution of the U-value of the frame to this overall thermal transmittance becomes totally negligible. As already mentioned, in case of a unit width of 2.4 m, the contribution of the thermal transmittance of the frame is already minimal compared to the contribution of the U-value of the glass.

Table 3: Influence of the type of steel section

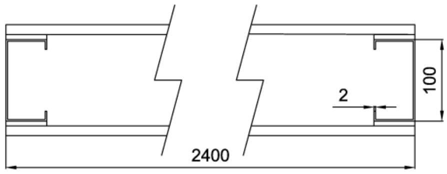
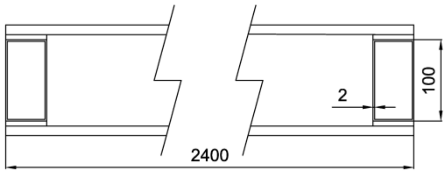
Simulation	Description		U-value	Difference to reference
			W/(m²K)	%
1	Reference		2.7788	-
2	Tubular section (t = 2 mm)		2.8061	+0.98

Table 4: Influence of the web height of the steel section

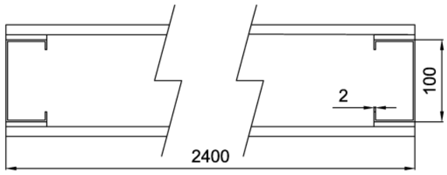
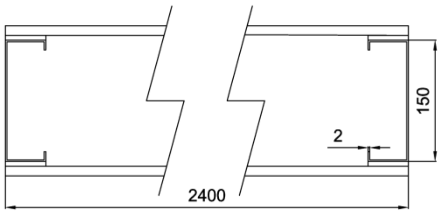
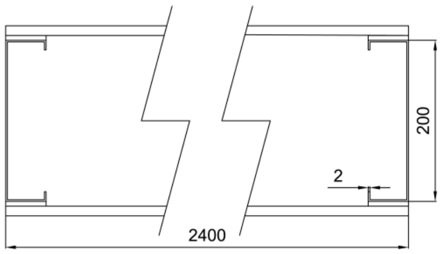
Simulation	Description		U-value	Difference to reference
			W/(m²K)	%
1	Reference		2.7788	-
6	Open section (h_w = 150 mm)		2.7721	-0.24
7	Open section (h_w = 200 mm)		2.7664	-0.45

Table 5: Influence of the thickness of the steel section

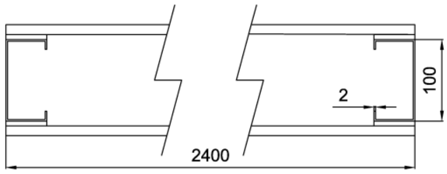
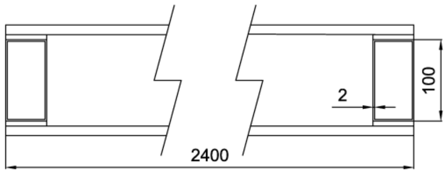
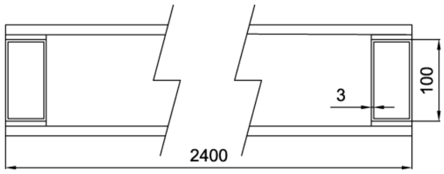
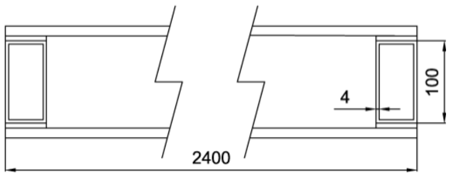
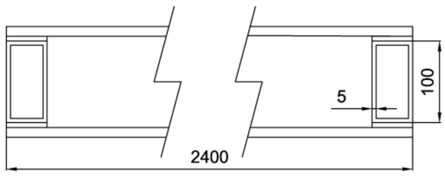
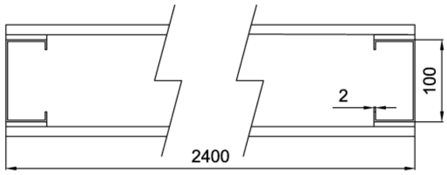
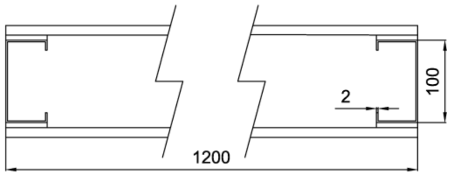
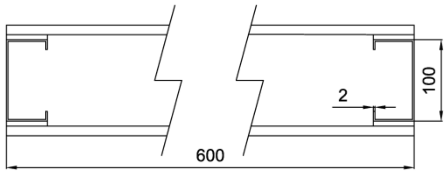
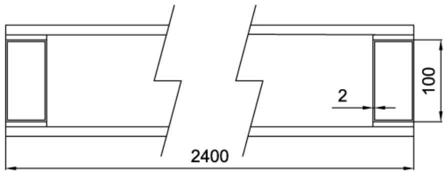
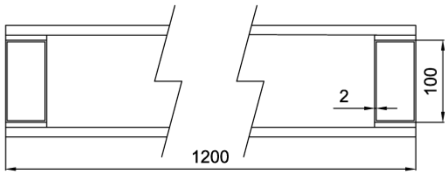
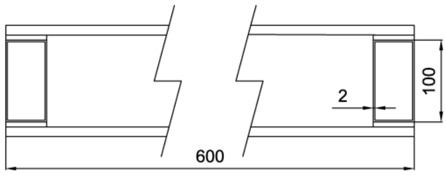
Simulation	Description		U-value	Difference to reference
			W/(m²K)	%
1	Reference		2.7788	-
2	Tubular section (t = 2 mm)		2.8061	+0.98
3	Tubular section (t = 3 mm)		2.8168	+1.37
4	Tubular section (t = 4 mm)		2.8232	+1.60
5	Tubular section (t = 5 mm)		2.8237	+1.62

Table 6: Influence of the width of the unit

Simulation	Description		U-value	Difference to reference
			W/(m²K)	%
1	Reference		2.7788	-
8	Open section (w = 1200 mm)		2.8338	+1.98
9	Open section (w = 600 mm)		2.9437	+5.93
2	Tubular section (w = 2400 mm)		2.8061	+0.98
10	Tubular section (w = 1200 mm)		2.8897	+3.99
11	Tubular section (w = 600 mm)		3.0555	+9.96

The thermal performance of the façade unit can be more efficiently enhanced by improving the thermal performance of the glazing. For standard cases, several solutions for this problem already exist, e.g. insulated glass units (IGU), vacuum glazed units (VGU), etc. Therefore, a simulation was performed in which the inner single glazing was replaced by a double glazing unit with a U-value of 1.30 W/m²K (Saint-Gobain 2015). The result was an astonishing decrease of 70.24% compared to the reference, which implies an overall U-value of 0.8270 W/(m²K) for the façade unit. Moreover, this configuration meets the requirement of a maximum U-value for the unit of 2.00 W/(m²K) (cfr. supra). Other possible configurations using these solutions are still under investigation. Also the determination of the contributions of the U-values of the glazing and the frame to the overall U-value is in progress to assure a maximum U-value for the glazing of 1.1 W/(m²K) (cfr. supra). Furthermore, possible connections between multiple hybrid cold-formed steel-glass façade units have to be designed and assessed for their mechanical and thermal performance. An example of such a connection is illustrated in Figure 5. However, from this research it is assumed that the effect of properly designed connections on the thermal performance of the façade will be minimal and that the contribution of the thermal transmittance of the glazing will be decisive, given the large glass area and the very reduced steel thickness and frame area. Of course, further research will be performed to confirm these suppositions and quantify with values.

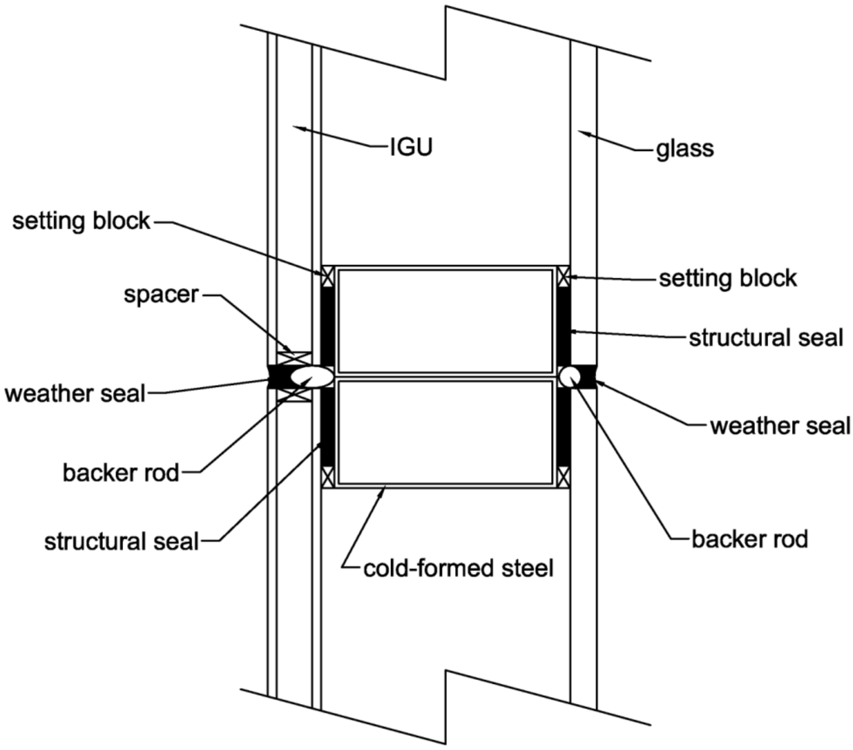


Figure 5: Detail of a possible connection between two hybrid cold-formed steel-glass structural closed-cavity façade units

Future work

In the near future, additional experimental tests on the structural silicone Sikasil® SG-500 will be executed to investigate the difference between the values for the thermal conductivity obtained in this research and the values provided by the manufacturer. New, monolithic specimens will be produced to mitigate the effect of possible air layers in between multiple adhesive layers and tested afterwards. Additional two-dimensional numerical simulations will enable the quantification of the individual U-values of the glazing and the frame of the unit. Other configurations of the glazing will be simulated to relate the obtained thermal performance to economic parameters and to optimise energy efficiency. Next, possible connections between different elements are designed and their mechanical and thermal performance evaluated by means of numerical modelling. A three-dimensional numerical models using computational fluid dynamics will be elaborated to model convection flow phenomena within the cavity and to assess its influence on the thermal behaviour of the unit. Furthermore, this 3D model it would be more reliable since it is able to fully model an entire unit and not only a 2D cross-section. The elaboration of an experimental program can then be elaborated to validate numerical models and to prove the efficiency of selected units. Racking tests and wind pressure/suction tests will enable an evaluation of the mechanical performance of basic units. Tests on these units in a Guarded Hot Box allow the measurement of their thermal performance. Taking into account the embodied energy of the units, a proposal for a structural closed-cavity façade unit with optimum energy efficiency combined with optimal structural performance will then be drawn. In the end, case studies in which the structural closed-cavity façade is compared to traditional double-skin façades will prove the economic, ecological and mechanical efficiency of the hybrid cold-formed steel-glass façade units. The obtained technological knowledge will be disseminated by means of papers in international journals and of conference papers.

ir. Bert Van Lancker (Visitor)

Date: 23/12/2015

Prof. Paulo Santos (Host)

Date: 23/12/2015

References

CEN (2006). “prEN 13947: Thermal performance of curtain walling. Calculation of thermal transmittance.” CEN, Brussels.

DIN (1979). “DIN 52612-1: Testing of thermal insulating materials. Determination of thermal conductivity by the guarded hot plate apparatus. Test procedure and evaluation of results.”. DIN, München.

EU (2002). “DIRECTIVE 2002/91/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2002 on the energy performance of buildings.” Official Journal of the European Communities, European Union, Brussels.

ISO (2007). “ISO 6946: Building components and building elements - Thermal resistance and thermal transmittance - Calculation method.” ISO, Geneva.

ISO (2008). “ISO 22007-2: Plastics -- Determination of thermal conductivity and thermal diffusivity -- Part 2: Transient plane heat source (hot disc) method.” ISO, Geneva.

NBN (2007). “NBN EN 13947: Thermal performance of curtain walling – Calculation of thermal transmittance.” Bureau of normalisation, Brussels.

NBN (2008a). “NBN B62-002: Thermal performances of buildings – Calculation of thermal transmittances of building components and building elements – Calculation of transmission and ventilation heat transfer coefficients.” Bureau of normalisation, Brussels.

NBN (2008b). “NBN EN ISO 10456: Building materials and products – Hygrothermal properties – Tabulated design values and procedures for determining declared and design thermal values (ISO10456:2007)(+AC:2009).” Bureau of normalisation, Brussels.

NBN (2008c). “NBN EN ISO 6946: Building components and building elements – Thermal resistance and thermal transmittance – Calculation method (ISO 6946:2007).” Bureau of normalisation, Brussels.

NBN (2011). “NBN EN 673: Glass in building – Determination of thermal transmittance (U-value) – Calculation method.” Bureau of normalisation, Brussels.

Saint-Gobain (2015). “SGG Planitherm® One T – Superior performance “single-stock” low-E glass.” Saint-Gobain Glass UK Ltd, Eggborough.

Sika (2008): “Sikasil® SG-500: Calculation Value Sheet.” Sika, Zürich.

Sika (2015): “Sikasil® SG-500: Product Data Sheet.“ Sika, Zürich.

THERM (2015). “THERM Finite Element Simulator”. Version 7.4.3.0 (21/09/2015). Lawrence Berkeley National Laboratory, University of California, Berkeley.