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Mistral Tower: Value of System Design, Manufacturing and Installation in Cold Bent SSG Units

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Use of cold-bent and warped glass units in unitized curtain walling is becoming a state-of-the art application. During the last years, such a global trend has challenged the design and engineering of glass units, frame elements as well as bonding joints in Structural Sealant Glazing (SSG) applications and has pushed for the investigation of material performance and calculation concepts, beyond available standards and guidelines. It is clear today that in SSG systems cold bending retention forces and differential displacements play a major role in the system design and need to be properly controlled. With reference to SSG joints, investigation has focused on proposing simplified equations to evaluate cold bending stress and studying relaxation and creeping behavior of Sikasil® structural silicones to exploit material performance beyond standard limits. Such investigation process allows identifying where opportunities for systems optimizations are and clarifies that effective cold-bending solutions cannot be uncoupled from new principles of system design, pre-manufacturing and installation. The development of Mistral Tower in Izmir offers the chance to evaluate in detail the impact of different frame solutions in combination with different production and installation methods and is used to present to system designers and façade producers valuable options and guidelines for approaching design of cold-bent units effectively. The use of slim adapter frame bonded to glass units and free to slide into load-bearing frame represents the basic requirement to limit cold bending effects on SSG joints, while minimizing production efforts. Valuable optimization results can be further achieved if bonding on either pre-shaped frame or pre-shaped frame/glass assembly is possible or if cold-bending stress can be limited in time by a clever production method in controlled conditions. Advanced FE analysis simulating SSG joints by hyperelastic material law validate preliminary stress evaluation, criteria selection for unit manufacturing and final design choices in Mistral Tower construction.

Keywords: Cold-Bending, SSG, Curved, Structural Silicone, Finite Element Modelling, Hyperelastic

1. Introduction

Mistral Izmir is a prestigious project in Izmir (Turkey) designed in 2011 by Progetto CMR – Massimo Roj Architects and promoted by the investment and vision of Mistral Construction, a partnership of leader businessmen in Izmir aiming at adding value to the real estate sector of the city.

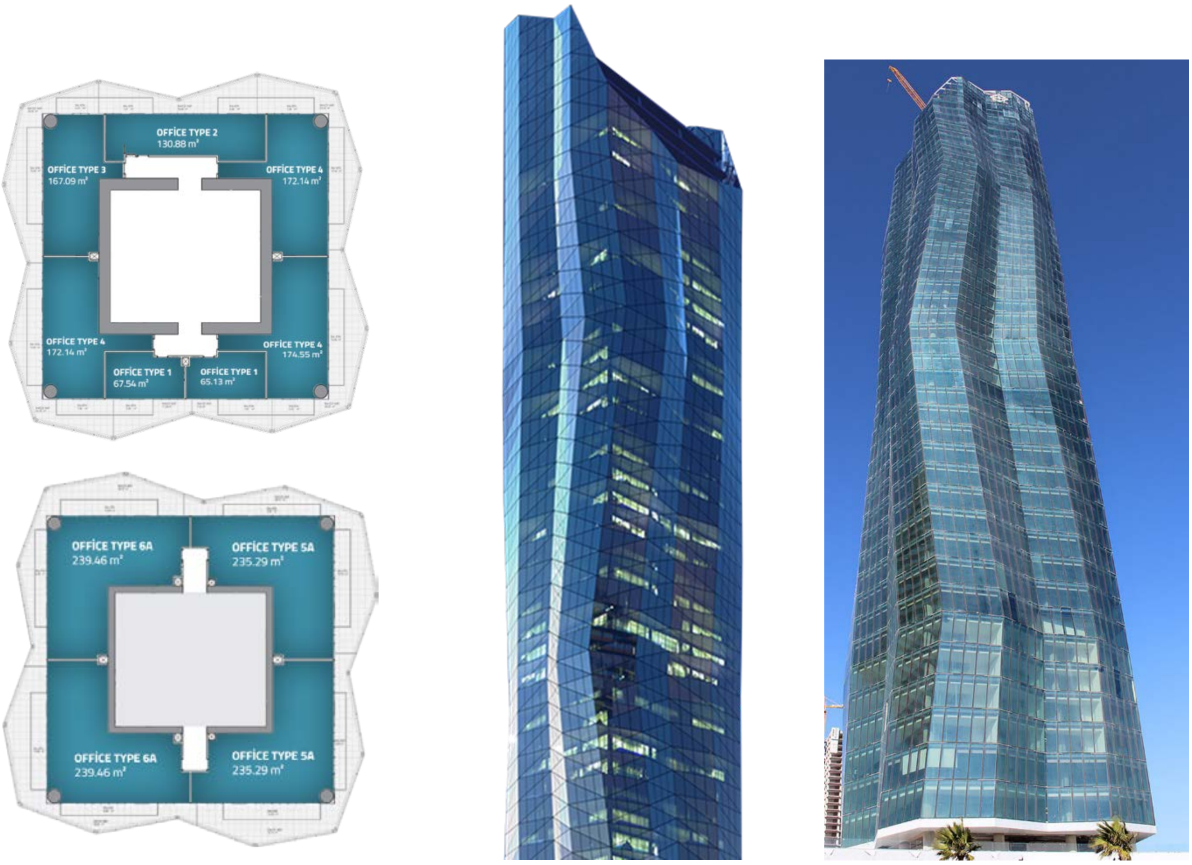
The project consists in the development of a Residential Tower and a Office Tower connected by a Shopping Center (Fig. 1), candidate to become landmarks of the city skyline due to their architectural shape and height.

Fig. 1 Mistral Izmir

This paper focuses on the design of the cold-bent glass façade of the Office Tower, a 46-floor 180m-high building being the tallest in Izmir.

The Tower envelope consists of a double skin façade used to improve sound and heat insulation of the enclosed environments, while providing comfortable offices surrounded by resting place and terraces of different shape (Fig. 2a). The variable layout of the building slabs – rotating at each floor level – poses immediately the challenge for the design of a cost-effective solution for the outer glass skin. At initial stage, the facade design relied on unitized glazed panels composed by flat triangular elements of different inclination to close the building consistently from floor to floor (Fig. 2b). Anyway, advanced parameterization analysis for façade optimization proved that such design approach led to production of a large amount of different elements and identified in a cold-bending solution the optimum way to proceed: by use of slight curvatures, a single rectangular façade element could be designed to develop the entire façade, by exploiting the benefits offered by serial cold-bending (Fig. 2c).

As in the majority of international projects where complex geometry and sophisticated layouts want to be emphasized by flowless surfaces and transparency, fixing of cold-formed glass panels by Structural Sealant Glazing (SSG) systems was the target, with the structural silicone adhesives having the function of ensuring the load-bearing connection between frame and glass units (Fig. 3).



a) b) c)

Fig. 2 The Office Tower: a) Examples of Slab Layout b) Initial and c) Final Design of the Outer Façade Skin.

2. Effects of Cold Bending on SSG Joints

The demand of emulating nature's complex and flowing layout by using curved or even biomorphic design combined with transparent panels and valuable surfaces is an increasing trend replacing conventional straight-lined and sharp-edged geometries in architectural design. That means glass units and their restraints have to fit curvilinear designs, what pushes the demand on curved and warped single glass, laminated glass as well as insulating glass units replacing more and more flat and polygonally shaped elements.

Curved architectural glass can be usually manufactured for the façade markets according to three main methods: hot bending, cold bending and bending by lamination (Dodd et al. 2007). When the use of slight curvatures and uniformly bent geometries is required, use of cold-bent glazing is usually recommended.

Cold-bending (and cold-warping) of facade elements usually consists in cold bending of monolithic glasses, laminated glasses or insulating glass units as well as the frames that retain them in the structure after they have been produced and assembled in a flat state. Compared to production and assembly of hot bent curved elements, this technique drastically reduces production timeframe and costs.

In this context, fixing of cold-formed glass panels to frame is usually obtained by the load-bearing bonding provided by structural silicone adhesives in Structural Sealant Glazing (SSG) systems, which enhance transparency and allow appreciating surface value. Despite cold-bending can be considered today a state-of-the-art application and designers and façade producers are getting more and more experienced with this technology, curved glass elements are still not standardized products and available standards and guidelines dealing with SSG systems (EOTA ETAG 002 2012, ASTM C 1401 2014) do not explicitly clarify how to deal with stress introduced into joints by cold-bending. Thus, this requires careful engineering analysis and deep understanding about material behavior.

During last years, the global trend of using cold-bent units has challenged the design and engineering of façade systems and has pushed for the investigation of material performance and calculation concepts beyond available standards and guidelines. With reference to SSG joints, investigation from Sika has focus on (Nardini et al. 2017, Doebbel et al. 2016):

- Proposing simplified equations to evaluate stress introduced into structural silicone joints due to cold bending
- Studying creeping and relaxation behavior of Sikasil® structural silicones to exploit material performance beyond standard limits.

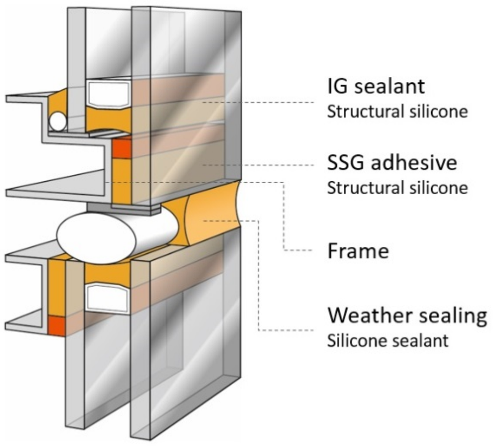


Fig. 3 Typical Structural Sealant Glazing (SSG) System ©.

2.1. Simplified Equations to Evaluate Cold Bending Stress into SSG Joints

Cold bending of flat SSG assembly (i.e. flat glass unit structurally bonded to flat frame) introduces significant reactions in the elastic silicone joints in the form of:

- Permanent tensile forces
  The permanent tensile forces are caused by restoring forces (back flipping) of displacement elastically imposed to the flat produced assembly and need to be properly withstood by the joint over its whole life cycle. Based on composition and geometry of the glass unit to cold bend, the restoring force can be calculated or experimentally determined using a dummy load used to deform it up to the required shape.
  In case of cold-bent elements where an out-of-plane displacement is imposed at one corner of the unit, such a dummy load can be evaluated considering it as applied at the same corner. The load magnitude will depend on the long-term and short-term performance of any interlayer used in laminated glass, on the behavior of the edge sealing system used for any insulating glass unit and finally on the displacement to achieve.
  Under the assumption of a linear tensile stress distribution along the bond line (Beer 2015, Nardini et al. 2017), the restoring force identified by the dummy load could then be distributed as an idealized triangular load along the panel edges (Fig. 4), so that stress along the bond line can be calculated by the simplified equation provided below:

$$\sigma = \frac{4.5 \cdot PL}{(H + W) \cdot b} \qquad (1)$$

With:

σ max. tensile stress on SSG joint due to cold bending
PL dummy load to deform the unit
H glass height
W glass width
b joint bite

Permanent tensile forces due to cold bending of flat produced assembly affect both the SG joints (to bond glass panel to frame) and the IG joints (secondary sealing of insulating glass units), as shown by Fig. 5.

Once a cold-bent system is defined, the tensile force F_{tot} transferred by the SG joint will be always higher than the tensile force F_{out} transferred by the IG joint.

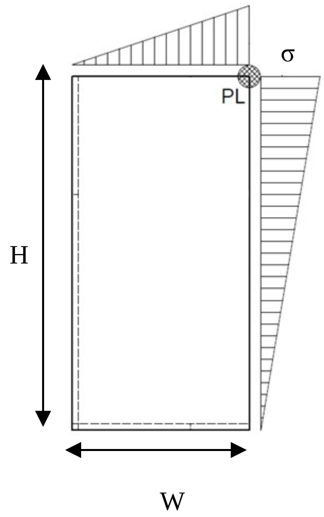


Fig. 4 Dummy load applied at unit corner and linear stress distribution.

- Permanent shear movements
  Cold bending of flat SSG assembly imposes rotations to the façade components, introducing differential displacements between bonded surfaces. Such displacements (s_{joint} and s_{seal} in Fig. 5b) are accommodated by the joints in the form of shear deformation.
  In case of cold-bent elements where an out-of-plane displacement is imposed at one corner of the unit, rotation of the bonded elements are maximum at the corners (Fig. 6) and can be estimated according to simplified Equation 2:

$$\alpha[rad] = 3.2 \frac{f}{2 \cdot L_{\min}} \qquad (2)$$

With:

α maximum rotation of the components
f maximum displacement imposed at the corner by cold-bending
L_{min} length of the shortest sides of the rectangular unit

Based on rotation, differential displacements occurring between bonded parts can be determined and shear stress into joint immediately calculated (Fig. 6):

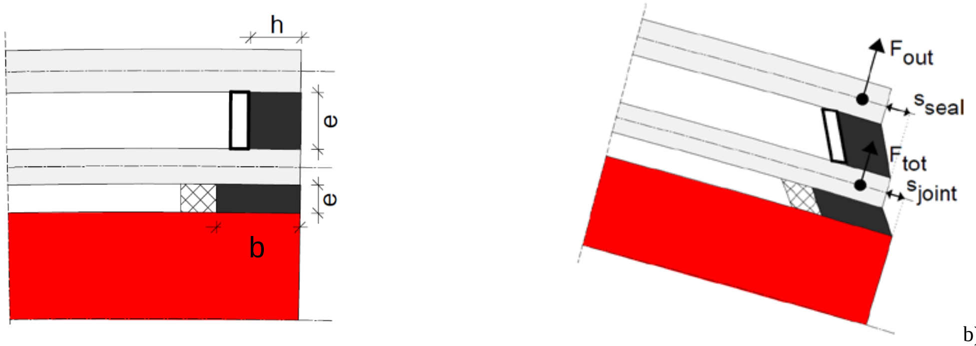
$$\Delta = \alpha[rad] \cdot \left(h_{S1\_b} + h_{S2\_b}\right) \tag{3}$$

$$\tau = \frac{\Delta \cdot G}{e} \tag{4}$$

With:

Δ	differential shear displacement between bonded parts
h_{S1_b}	distance of barycenter of cross section 1 to bonded area
h_{S2_b}	distance of barycenter of cross section 2 to bonded area
e	joint thickness
G	adhesive shear modulus

As shown by Fig. 5, permanent shear movements due to cold bending of flat-produced assembly affect both the SG joints and the IG joints.



b)

Fig. 5 a) Initial shape of SG and IG joints b) Deformed shape of SG and IG joints after cold bending of flat assembly ©.

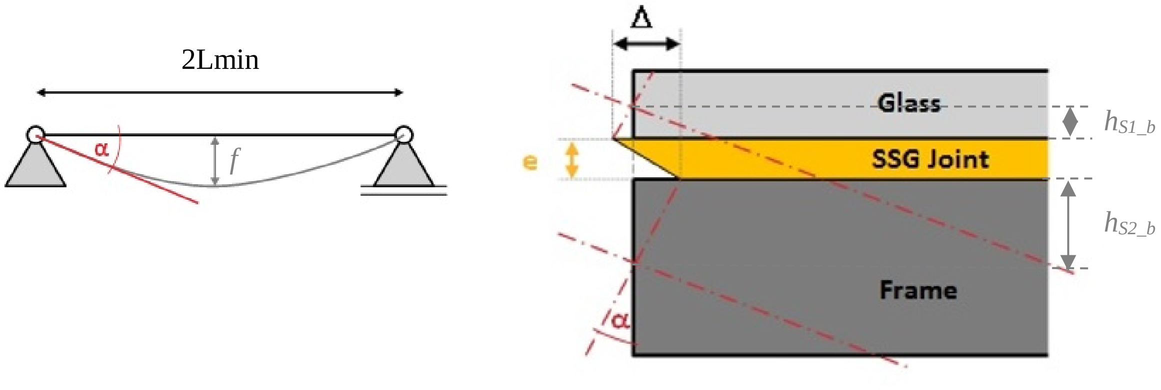


Fig. 6 Differential shear displacement Δ imposed to joints due to rotation produced by cold bending ©.

2.2. Performance of Sikasil® Silicones under Permanent Shear Deformation due to Cold Bending

As mentioned in Section 2.1, cold bending of flat assembly introduces permanent shear movements into joints. This arises the question about performance limitations of silicone adhesives exposed to permanent share deformations, which does not find any answer in the available guidelines dealing with SSG systems (i.e. EOTA ETAG 002 2012, ASTM C 1401 2014).

EOTA ETAG 002 defines a creep test with joints exposed to long-term shear in superposition with cyclic tensile loading and helps to give indications about long-term performance of structural silicones. Such a creep test requires massive restrictions on residual shear deformation of joints after complete unloading, besides an adequate material resistance under permanent loading. Final target of such a creep test is to define what the influence of permanent shear stress is on SSG joints, to simulate the case of dead load unsupported systems where joints need to withstand permanent weight and short-term wind actions.

Despite this, it should be noted that creeping concept cannot be applied to the case of long-term displacements imposed to SG joints by cold-bending; indeed, these are permanent but always limited in magnitude as related to a one-time set up and do not increase over the life cycle – thus the risk of creeping is structurally not existent. Instead, a concept for dealing with phenomena of stress relaxation due to permanent deformation should be defined.

Table 1 summarizes updated strengths that can be used for main Sikasil® silicone adhesives when dealing with cold-bending, based on investigation and test results described in Nardini et al. 2017.

Table 1: Extended range of strength values for design.

Product	EOTA ETAG 002					
	σ_{Des} [MPa]	τ_{Des} [MPa]	τ_{∞} [MPa]	σ_{∞} [MPa]	$\tau_{\infty,Relax}$ *) [MPa]	G [MPa]
Sikasil® SG-500	0.14	0.105	0.0105	0.014	0.0315	0.50
Sikasil® SG-550	0.20	0.130	0.013	0.020	0.039	0.63
Sikasil® IG-25	0.14	0.101	0.0101	0.014	0.030	0.73
Sikasil® IG-25 HM Plus	0.19	0.130	0.011	0.019	0.033	0.86

*) Shear stress accounting for relaxation. To be used only for imposed permanent deformation.

2.3. Calculation Approach

The strength offered by structural silicones depends on the duration of the load applied.

Based on this, an optimized calculation approach can be defined to exploit material performance in demanding applications beyond available standards and guidelines.

For calculating the existing utilization level of the elastic bonding joints and ensure durable performance, the expected duration of different load impacts should be evaluated at first. Then, all load combinations associated to different timeframe where simultaneous loads are applied should be defined and stress evaluated in relation to relevant design strength.

- Long-term load combination
  Joint utilization level must be evaluated in the long-term, considering all permanent loads that apply to joint (i.e. dead load, cold-bending, etc.) and evaluating the stress they introduce in relation to its long-term design strength. With reference to EOTA ETAG 002 2012, strength values provided in Table 1 can be used.

$$\mu_{shear\_\infty} = \frac{\tau_{perm\_1}}{\tau_{\infty}} + \frac{\tau_{perm\_2}}{\tau_{\infty}} + \ldots + \frac{\tau_{perm\_i}}{\tau_{\infty}} \leq 1.0 \tag{5}$$

$$\mu_{tensile\_\infty} = \frac{\sigma_{perm\_1}}{\sigma_{\infty}} + \frac{\sigma_{perm\_2}}{\sigma_{\infty}} + \ldots + \frac{\sigma_{perm\_i}}{\sigma_{\infty}} \leq 1.0 \tag{6}$$

$$\mu_{\infty} = 0.5\mu_{tensile\_\infty} + \sqrt{\left(\frac{\mu_{tensile\_\infty}}{2}\right)^2 + \mu_{shear\_\infty}{}^2} \leq 1.0 \tag{7}$$

- Short-term load combination
  Joint utilization level must be evaluated based on different short-term timeframes.
  For each timeframe, loads that can simultaneously apply on joint should be identified.
  Relevant stress into joint must be evaluated in relation to design strength of relevant short-term duration.
  With reference to EOTA ETAG 002 2012, strength values provided in Table 1 can be used.

$$\mu_{shear\_ST} = \frac{\tau_{ST\_1}}{\tau_{Des}} + \frac{\tau_{ST\_2}}{\tau_{Des}} + ... + \frac{\tau_{ST\_i}}{\tau_{Des}} \leq 1.0 \tag{8}$$

$$\mu_{tensile\_ST} = \frac{\sigma_{ST\_1}}{\sigma_{Des}} + \frac{\sigma_{ST\_2}}{\sigma_{Des}} + ... + \frac{\sigma_{ST\_i}}{\sigma_{Des}} \leq 1.0 \tag{9}$$

$$\mu_{ST} = 0.5\mu_{tensile\_ST} + \sqrt{\left(\frac{\mu_{tensile\_ST}}{2}\right)^2 + \mu_{shear\_ST}{}^2} \leq 1.0 \tag{10}$$

A flat assembly which is cold-bent after glass and frame have been bonded will be exposed to permanent load combination and even multiple short-term load combinations; for all load combinations identified, all relationships given in Equations 5-10 must be satisfied.

3. Mistral Tower: System Details and Boundary Conditions

Typical façade elements of Mistral Office Tower consist of a rectangular double glazed unit 1528mm x 4000mm (width x height), composed by two laminated glass panes 8mm thick (outer side) and a monolithic glass pane 8mm thick (inner side) spaced by a cavity 16mm deep.

In order to maximize transparency, the double glazed unit needs to be structurally bonded to aluminum profiles applied along all four sides.

The dead load of all glass panes can be permanently supported by mechanical means, so that during service life no permanent loads due to weight need to be transferred by the structural silicone joints.

The façade components are required to withstand a typical wind load of 2.50 kPa, reaching maximum values up to 4.0 kPa in local areas of the Tower.

Maximum temperatures expected for glass panels and aluminum frames during service life are 80°C and 55°C according to ETAG 002.

In order to fit the building design intent, a maximum out-of-plane displacement of +32mm or -32mm needs to be imposed at one of the top corners of each façade element by cold-bending.

FE analysis allows to evaluate the magnitude of the dummy load to apply at the top corner of the elements to cold-bend them up to the required level (Fig. 4-5):

- F_{tot} = 310 N Short-term force to cold-bend the IG unit
- F_{tot} = 120 N Long-term force to cold-bend the IG unit
- F_{out} = 220 N Short-term force to cold-bend the outer glass pane
- F_{out} = 60 N Long-term force to cold-bend the outer glass pane

The analysis took into consideration the specific geometry of the IG unit, its glass composition, the properties of the laminated glass interlayer and the stiffness of the IG edge sealing system.

3.1. Initial Design

The initial design of the façade elements relied on a traditional way of dealing with cold-bent systems. The idea was to assemble and install each element as follows:

- A flat IG unit could be properly positioned on spacer tapes already applied on a flat aluminum frame;
- The gap between frame and glass could be filled in by structural silicone Sikasil® SG-500;
- Once the adhesive joints were fully cured, the bonded assembly could be moved on site;
- On site, an out-of-plane displacement of 32mm could be imposed by cold-bending to specified corner of the element, to shape and install it.

Fig. 7a provides a detail of the initial design; an aluminum profiles 185mm deep bonded to the IG unit was included.

As explained in Section 2.1, described cold-bending procedure introduces permanent tensile forces and permanent displacements on SG and IG joints (Fig. 5b). Based on given system geometry, Equations 2-3 allow to evaluate that a shear differential displacement Δ = 3.2mm needs to be accommodate by the SG joint, requiring a minimum joint thickness of at least 51mm by Sikasil® SG-500 – although it is considered that shear material performance are exploited up to $\tau_{\infty,relax}$ strength values.

It is immediately clear that such SG joint thickness is unreasonable and opportunity for joint optimization need to be found outside any optimized calculation procedure and/or demand on pure material performance.

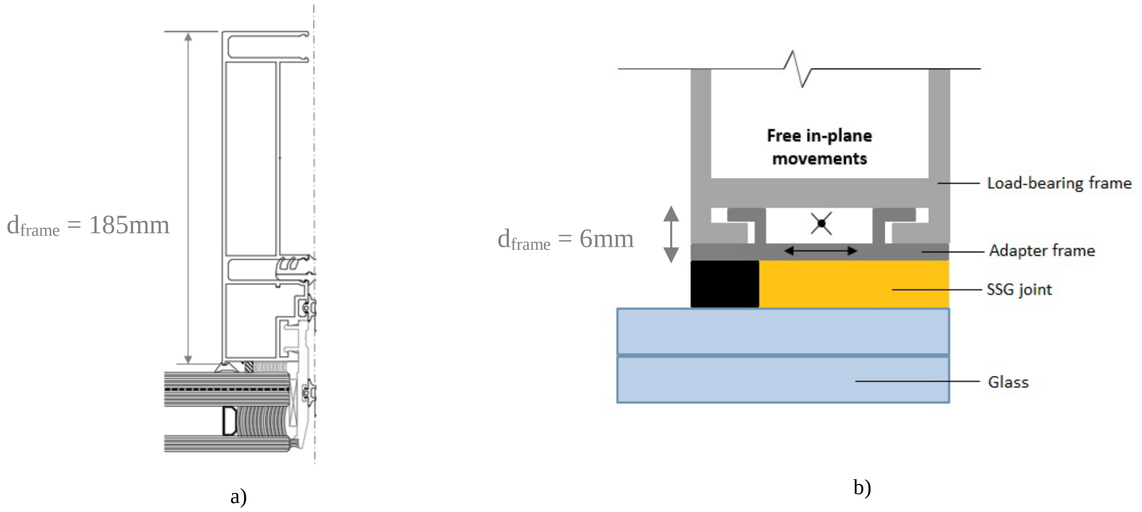


Fig. 7 a) Initial Design of System Detail and b) Optimized Design Including Slim Adapter Frame Free to Slide.

3.2. SSG Joint Optimization by Frame Design

Equations 2-4 clarify immediately that the distance between barycenters of bonded components – which defines the position of their bending axis – plays a major role in defining the magnitude of differential displacement to be accommodated by the SG joints; with regard to this, the cross sectional depth of the aluminum profile has for sure the higher impact. Thus, reducing the depth of the bonded profile offers immediately the opportunity to reduce significantly the minimum SG joint thickness.

Based on such considerations a second façade system was developed and evaluated, including IG units bonded to slim aluminum adapter profiles 6mm deep. Compared to assembly method described in Section 3.1, the idea was to assemble and install each element as follows:

- On factory, the flat IG unit could be preliminary bonded to the slim aluminum frame by structural silicone Sikasil® SG-500;
- Once the joints were fully cured, the bonded assembly could be cold bent up to the required level and mechanically fixed to load-bearing profiles either on factory or on site.

The new design approach allows for a massive joint thickness reduction down to 6mm by Sikasil® SG-500, due to the cold-bending differential displacement highly reduced to approx. 0.24mm and improved shear strength $\tau_{\infty,Relax}$ Considering all loads involved during system service life (Section 3) and wind loads of 2.50 kPa, a minimum SG joint dimensions of 25mm x 8mm (bite x thickness) by Sikasil® SG-500 is required (Table 2 and 3).

It has to be noted that in cold bent systems using a slim profile is valuable if it is ensured that it is free to slide and rotate around its barycenter during the cold bending phase. In other words, it does not make sense to fix mechanically the flat assembly to the main load-bearing frame if it is not cold bent yet. As a consequence, first manufacturing and installation option relied on:

- bonding the flat slim profile to the flat IG unit on factory and move the assembly on site when joints fully cured,
- cold bending such assembly on site,
- fix it mechanically to the main load-bearing frame already installed on the main building structure.

Anyway, if one considers that reducing the bonded profile cross section has only the target to minimize the distance between component bending axis, it is clear that system manufacturing and installation can be simplified by designing a mechanical connection between main profile and slim profile that can ensure free sliding of the slim profile with regard to the load bearing frame.

As a consequence, the use of a slim adapter frame bonded to the glass unit and free to slide into load-bearing frame (Fig. 7b) represents a basic requirement to limit cold bending effects on SG joints, while minimizing production and installation efforts. On factory, the flat slim adapter frame already inserted into the main frame can be bonded to the flat IG unit; after joints are completely cured, the assembly can be moved and cold-bent on site for installation.

3.3. SSG Joint Optimization by Manufacturing Method

Additional options for actively influencing the magnitudo of shear movements Δ in the elastic SG joints exist also by implementating different cold-bending procedures:

- A very effective way to null completely the permanent shear stress in the SG joint due to cold bending is using hot-bent frame members, so that only the IG unit needs to be cold bent.
  Independently from the cross-sectional depth of the frame profile, the glass unit can be cold-bent on the pre-shaped frame and temporarily fix to it by mechanical devices; application of the SG joint can follow. After the adhesive has completely cured, mechanical devices can be removed.

  As result, tensile restoring forces will stress the joints but introduction of permanent shear stress due to cold bending will be prevented permanently (Fig. 8a).

  Based on façade configuration and loads involved during service life (Section 3), such manufacturing procedure allows reducing SG joint dimensions by Sikasil® SG-500 to 18mm x 8mm (Table 2 and 3) under maximum wind load of 2.50 kPa.

- Another option to limit the permanent shear stress in the SG joint due to cold-bending is to temporary fix the IG unit to the frame in the flat state by mechanical devices and cold bend them; after that, application of the SG joint can follow. When adhesive is completely cured, the assembly can be moved to site in its deformed shape and installed. Once installed, mechanical devices used for initial manufacturing can be removed.
  As in previous case, tensile restoring forces will stress the joints but no permanent shear stress due to cold bending will be applied (Fig. 8a). As a consequence, same SG-joint dimensions defined above are required.

3.4. SSG Joint Optimization by Installation Method

A valuable option to limit the permanent shear stress in the SG joints due to cold bending is to temporary fix the cold bent IG unit by mechanical devices to a cold bent frame; after that, application of the adhesive can follow. Once adhesive is fully cured mechanical devices can be removed.

At this stage, shear stress due to elastic back flipping displacements between bonded parts will cause shear stress into the SG joint.

Anyway, such assembly will have to be transported to site and there cold-bent again for installation. That means that duration of cold-bending shear stress will be limited only to the timeframe from production (removal of temporary fixing between deformed IG unit and frame) to installation.

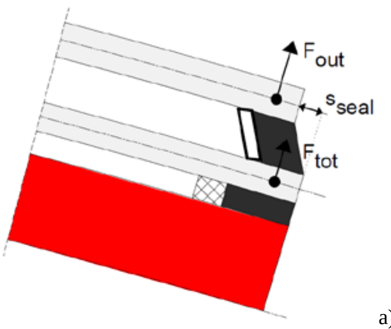
It is immediately clear that criteria for controlling such timeframe exist in order to minimize cold-bending effects on SG joints:

- The shorter the timeframe, the shorter the shear stress duration and the lower the impact on SG joint dimensions (the higher the adhesive shear strength offered)
- The lower the temperatures arising on frame and glass during such timeframe, the lower the simultaneous differential displacements occurring between bonded parts due to thermal dilatations

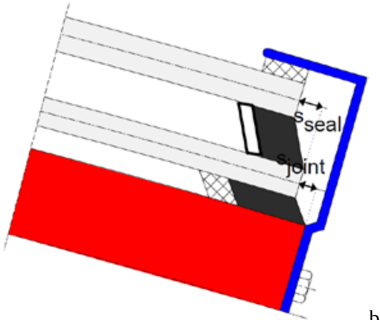
Section 2.3 and Equations 5-10 clarify that specific load combinations evaluating stress into the SG joint based on different timeframes and load durations should be implemented:

- Load case 1 (LC1)
  Configuration: Façade in service life
  Load duration (timeframe): Permanent
  Load combination: Cold bending effect (restoring tensile forces)
- Load case 2 (LC2)
  Configuration: Façade in service life
  Load duration (timeframe): Short-term
  Load combination: Cold bending effect (restoring tensile forces) + Wind Load + Thermal load_1
- Load case 3 (LC3)
  Configuration: from production (removal of temporary mechanical devices) to installation
  Load duration (timeframe): limited to 168 hours
  Load combination: Cold bending effect (differential shear displacement) + Thermal load_2

In Mistral Tower system, implementing the described installation and cold-bending procedure could allow reducing the SG joints dimensions to minimum 18mm x 8mm by use of frame 185mm deep (Table 2 and 3); this considering a maximum temperature of 50°C for frame and glass during the timeframe associated to load case 3 and ensuring elements stored in horizontal position.



a)



b)

Fig. 8 Deformed joints for system where adhesive is applied a) after frame and IG unit has been cold bent b) on flat assembly which is then cold bent and equipped with load-bearing mechanical devices to retain the IG unit.

3.5. SSG Joint Optimization by Combined Methods

Cold-bending procedure described in Section 3.4 combined with frame design consideration provided in Section 3.2 gives the chance to reduce further SG joint dimensions (thickness).

As temporary shear displacements are introduced into the joints due to cold bending, it is obvious that cross sectional depth of the bonded profile has an impact on SG joint dimensions. Of course, the shorter the displacement duration, the lower the impact of cross sectional depth on joint.

Considering same conditions and cold-bending procedure mentioned in Section 3.4 but including a slideable adapter frame 6mm thick, SG joint by Sikasil® SG-500 could be applied according to minimum dimensions of 21mm x 7mm (Table 2 and 3).

3.6. Final Design, Manufacturing and Installation Procedure adopted in Mistral Tower

With reference to Mistral Tower, Table 2 quantifies the benefits offered by the different optimization methods described in previous sections, which propose different frame design, manufacturing and installation methods for minimizing SG joint thickness due to cold bending.

Opportunity for reducing SG joint bite also exist. A typical strategy is using permanent mechanical devices to restrain the glass unit to the frame (Fig. 8b), so that no permanent tensile forces due to cold bending are transferred to the joints. Anyway, using such devices was excluded in Mitsral Tower due to the aesthetical impact on final facade.

System described in Section 3.4 was finally selected for design and construction of the outer skin façade.

Table 2: Effects of Cold Bending on SG Joints depending on Design, Manufacturing and Installation Method.

Design, Manufacturing and Installation Method	Tensile Force due to Cold Bending			Differential Displacement due to Cold Bending		Minimum SG Joint Dimensions due to Cold Bending Sikasil® SG-500	
	Profile depth [mm]	Load [N]	Duration [-]	Δ [mm]	Duration [-]	b [mm]	e [mm]
Flat IGU bonded to flat frame and then cold bent (Section 3.1)	185	310 120	Short-term Permanent	3.2	Permanent	N/A	51
Flat IGU bonded to flat frame and then cold bent (Section 3.2)	6	310 120	Short-term Permanent	0.24	Permanent	12	6
IGU cold-bent on shaped frame. Adhesive applied on deformed shape. Assembly transported and installed in deformed shape. (Section 3.3)	185	310 120	Short-term Permanent	0.0	Permanent	7	6
IGU cold bent on shaped frame. Adhesive applied on deformed shape. Assembly transported and stored in flat shape and than cold-bent again for installation. (Section 3.4)	185	310 120	Short-term Permanent	3.2	Short-term (max.168 h)	16 [13] *	16 [7] *
IGU cold bent on shaped frame. Adhesive applied on deformed shape. Assembly transported and stored in flat shape and than cold-bent again for installation. (Section 3.5)	6	310 120	Short-term Permanent	0.24 **	Short-term (max.168 h)	7	6

* For this manufacturing and installation configuration, the differential displacement imposed by cold bending is associated to a single event limited in duration. Based on test results summarized in Nardini et al. 2016, the movement capability of 12.5% certified for Sikasil® SG-500 can be exploited. As a consequence, a minimum joint thickness of 7mm would be required outside EOTA ETAG 002 recommendations – considering only cold bending effect.

** Excluding any thermal dilatation.

Table 3: Min. SG joint dimensions required for Cold-Bent System,
considering all loads occurring during service life based on relevant load combinations (Section 2.3 and 3)

Design, Manufacturing and Installation Method	Minimum SG joint dimensions required [bite x thickness] Sikasil® SG-500		
	Profile depth [mm]	Wind Load 2.50 kPa	Wind Load 4.00 kPa
Flat IGU bonded to flat frame and then cold bent (Section 3.1)	185	> 51mm x 51mm	N/A
Flat IGU bonded to flat frame and then cold bent (Section 3.2)	6	25mm x 8mm	28mm x 10mm
IGU cold-bent on shaped frame. Adhesive applied on deformed shape. Assembly transported and installed in deformed shape. (Section 3.3)	185	18mm x 8mm	27mm x 8mm
IGU cold bent on shaped frame. Adhesive applied on deformed shape. Assembly transported and stored in flat shape and than cold-bent again for installation. (Section 3.4)	185	18mm x 8mm *)	27mm x 8mm *)
IGU cold bent on shaped frame. Adhesive applied on deformed shape. Assembly transported and stored in flat shape and than cold-bent again for installation. (Section 3.5)	6	21mm x 7mm *)	27mm x 8mm *)

*) For this manufacturing and installation configuration, the differential displacement imposed by cold bending is associated to a single event limited in duration. As a consequence, in Load Case 2 of Section 3.4 adequacy of the joint thickness can be evaluated outside EOTA ETAG 002 recommendations exploiting the movement capability of 12.5% certified for Sikail® SG-500 (Nardini et al. 2016).

4. Validation by Finite Element Method

4.1. Finite Element Model

To estimate the local stresses within the recommended SG joint dimensions and to check the assumptions in Section 3, numerical analysis was made. The numerical analyses were performed with the multiphysics finite element code ANSYS (version 18.2). All parts of the façade system (aluminum profiles, glass, interlayer, SG and IG joint) were idealized using volume elements. To estimate the stresses in an appropriate way, isotropic hyperelastic material models for the structural silicones are used, as this resembles the stress-strain behavior in good approximation (Clift 2013, Staudt 2013). The material parameters are given in (Sika 2013). The finite element model used for the calculation and the meshing is shown in Figure 9. The following assumptions were made for the numerical calculation in Ansys:

- Volume elements Solid 186 for all components: SOLID186 is a higher order 3-D 20-node solid element that exhibits quadratic displacement behaviour
- Rectangular cross-section with equivalent bending stiffness to the actual substructure for the aluminium profiles
- Brick volume elements with an aspect ratio close to 1 and a meshing size of 4 mm for the relevant SG joints
- Polynomial (n=2) hyperelastic model for the SG joints according to (Sika 2013)
- Linear elastic material behavior for aluminum, IG joint, glass and PVB interlayer
- Bonded contact between SG joint and glass, between SG joint and aluminum profile and between IG joint and glass
- Local nodal support in the corners of the supporting frame (Figure 10a)

The three load cases defined in Section 3.4 were considered in the numerical calculation. The following load case-related assumptions were made for this purpose:

- Cold bending was idealized as horizontal support displacement of 32 mm (y-direction) at one of the top corners of the aluminum-substructure (LC 1 to 3)
- Due to the continuous stress by cold bending (LC 1 and 3), no shear transfer was taken into account for the laminated safety glass by using a shear modulus of G = 0.01 MPa
- To estimate the stresses caused by thermal loading (LC 2) the lower corners of the glass pane were fixed in z-direction (Figure 10b) in a second load step
- To estimate the stresses due to wind suction, the loading has been splitted to the inner and outer glass panes according to the stiffness of each pane (LC 2)
- Due to the short load duration of the wind load, a partial shear transfer was taken into account for the laminated safety glass by using a shear modulus of G = 3 MPa (LC 2)

For the calculation of LC 1 (permanent cold bending under service conditions) and LC 2 (permanent cold bending under service conditions + wind load + thermal load) an aluminum profile with negligible thickness was used. The bending stiffness was adjusted to the actual substructure. As described in section 2.1, this minimizes the differential shear deformation Δ between frame and glass. Accordingly, the normal stresses dominate and the condition corresponds to an adhesive joint applied with glass and frame in the deformed state (e.g. Section 3.4). However, in the calculation of LC 3 (temporary cold bending during assembly), the aluminum profile was modeled with the actual construction height, as the joint is not only subjected to the restoring forces of the glass, but also to the differential shear deformations caused by the deformation of the complete element back to its initial state.

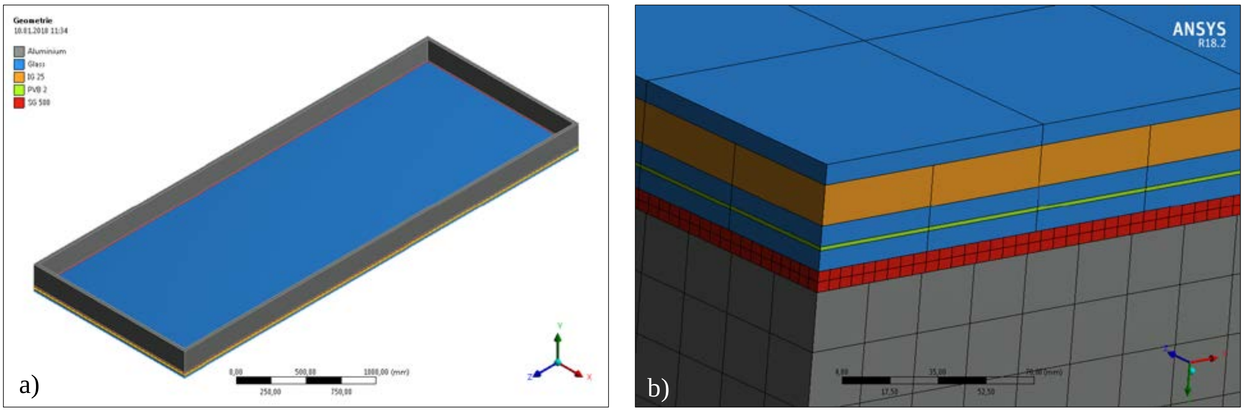


Fig. 9 Finite element model: a) overall view of the geometry, b) meshing of the model

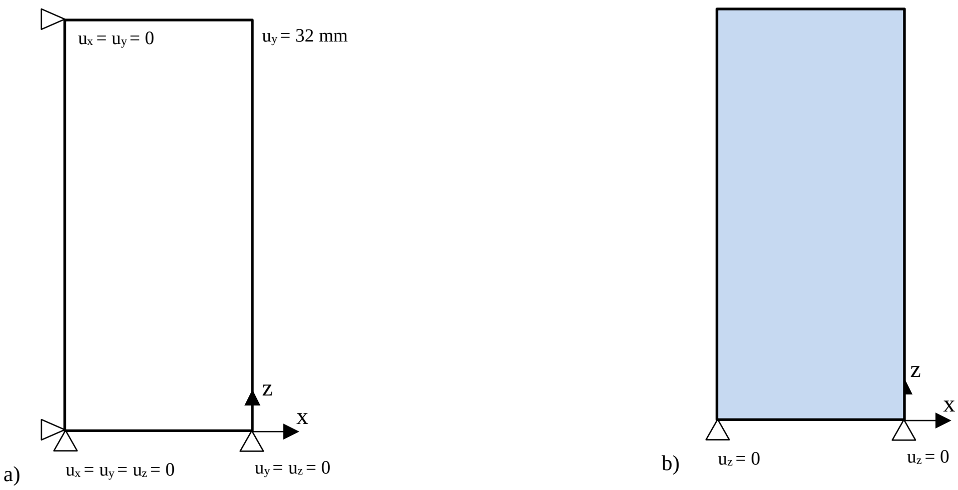


Fig. 10 Schematic representation of the supporting conditions of the finite element model: a) support of the aluminium substructure, b) additional support of the glass pane in case of temperature loading, which was taken into account in a second calculation step.

The dead load of the glass is removed by setting blocks at the lower edge of the glass. This prevents the glass pane to expand in this direction in case of temperature changes. Correspondingly, the support conditions have to be different from those for forced installation. During the bending process the glass pane is able to move in all directions. In order to calculate the stresses resulting from the load combination of cold bending, wind load and temperature, the analysis must be divided into two calculation steps. In an initial calculation step, the forced deformation is applied. In the second calculation step the lower glass edge has to be fixed and the temperature and wind load is applied.

4.2. Results

The results of the numerical simulations are summarized in Table 4 and Figure 11 to 13. In Table 4 the differential shear deformations Δ between the inner glass pane and the supporting frame, the maximum equivalent stresses in the SG joint $\sigma_{V,max}$ for the three load cases and the two investigated material models are given. Please note that these do not necessarily occur at the same location.

The calculated equivalent stresses are compared to the design values $\sigma_{des,FEM}$. The Utilization $\mu_{ST} = \sigma_{V,max} / \sigma_{des,FEM}$ is calculated on the basis of the equivalent stresses, as the design of SG joints using the finite element method are nowadays based on design criteria taking into account the equivalent stress (Equation 7). In scientific research, however, new models for the description of failure with finite fracture mechanics (Rosendahl 2017) and cavitation failure (Drass 2018) are investigated. The values $\sigma_{des,FEM}$ are design values according to ETAG 002 (Table 1), which are increased by a factor of 6/4. This increase was chosen, as the design according to ETAG 002 only provides a simplified design concept, which is based on technical stresses. When stress is determined by finite element analysis with volume elements, true stresses are calculated, which are significantly higher than the technical stresses. This justifies the reduction of the safety level from 6 according to ETAG 02 to 4 as is recommended by the adhesive suppliers (Sika 2017).

From the results it can be seen that the permanent stresses from the cold bending process are significantly lower than the temporary stresses during installation (Figure 12). The forced deformation results in permanent stresses of about 0.015 MPa and temporary stresses during installation of about 0.205 MPa. This demonstrates the potential that can be achieved by selecting an appropriate manufacturing process and confirms the chosen method.

Under wind load and temperature as well as temporarily during installation the joint ultilization level is approximately 1. This shows that the joint geometry has been selected efficiently and confirms qualitatively the analytical pre-measurement of the SG joints in Section 3.

Table 4: Summary of the results of the finite element calculations

Model	Load case [No]	Δ [mm]	$\sigma_{V,max}$ [MPa]	$\sigma_{des,FEM}$ [MPa]	μ_{ST} [-]
Initial State *Polynomial (n=2)*	1	0.13	0.015	0.021	0.71
	2	0.83	0.223	0.210	1.06
	3	1.01	0.205	0.210	0.98
Simulation of stress relaxation *adjusted Neo-Hookean*	1	0.13	0.010	0.021	0.48
	2	0.84	0.176	0.210	0.84
	3	-	-	-	-

However, Table 4 and Figure 12 also indicate that the numerically determined differential shear deformations are significantly lower than the analytically calculated values given in Table 3, since the numerical calculation of the temporary cold bending process Δ is approximately 0.8 mm. By the analytical solution a value of 3.2 mm could be derived.

In order to investigate the influence of stress relaxation from the permanently applied forced deformation on the stress in the SG joint, LC 1 and 2 were evaluated in addition to the material parameters according to (Sika 2013) with an adapted hyperelastic material model. A Neo-Hookean material model was chosen, whose parameters (μ = 0.41 MPa, D = 0) were adapted to the shear modulus given in Table 1. The calculation with the material model after (Sika 2013) can be considered as a simulation of the initial state, whereas the calculation with the adapted material model simulates the service life state. The results of the calculation (Figure 13 and Table 4) show that the stress in the SG joint decreases by about 30% over time.

Furthermore, for verification of the calculation approach described in Section 3, the influence of the frame height on the stresses in the SG joint was examined. For this purpose, the profile height was varied in the finite element calculation. The results are shown and compared to the analytical solution (Equation 3 and 4) in Figure 14. It can be seen that there is a linear relationship between the profile height and the resulting stress and that the stress increases with increasing profile height. The increase in stress for very low profile heights results from the decrease in bending stiffness, which was not adjusted for this calculation. The results of the numerical simulation are qualitatively and quantitatively consistent with the analytical solution. The analytical solution, however, slightly overestimates the stress and is therefore on the safe side for the dimensioning.

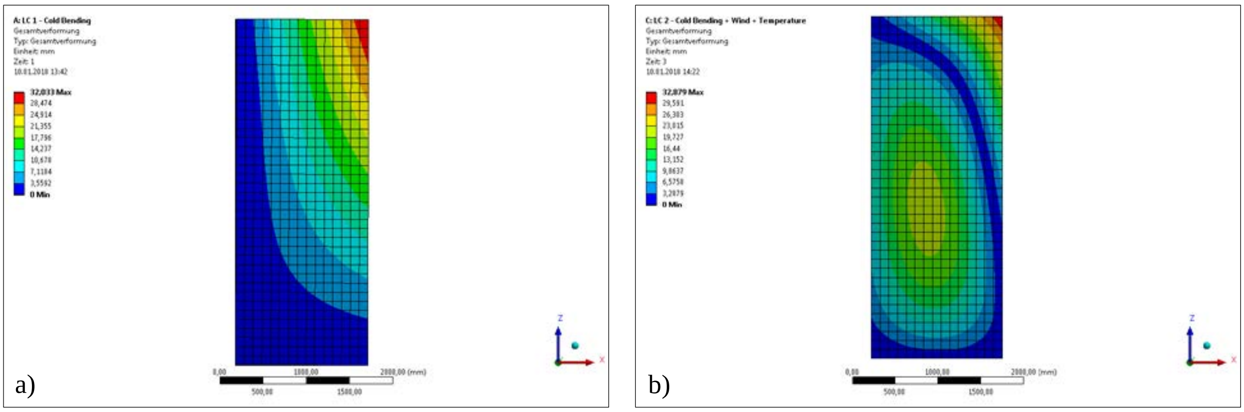


Fig. 11 Deformation of the façade elements: a) LC 1 cold bending, b) LC 2 cold bending + wind + temperature

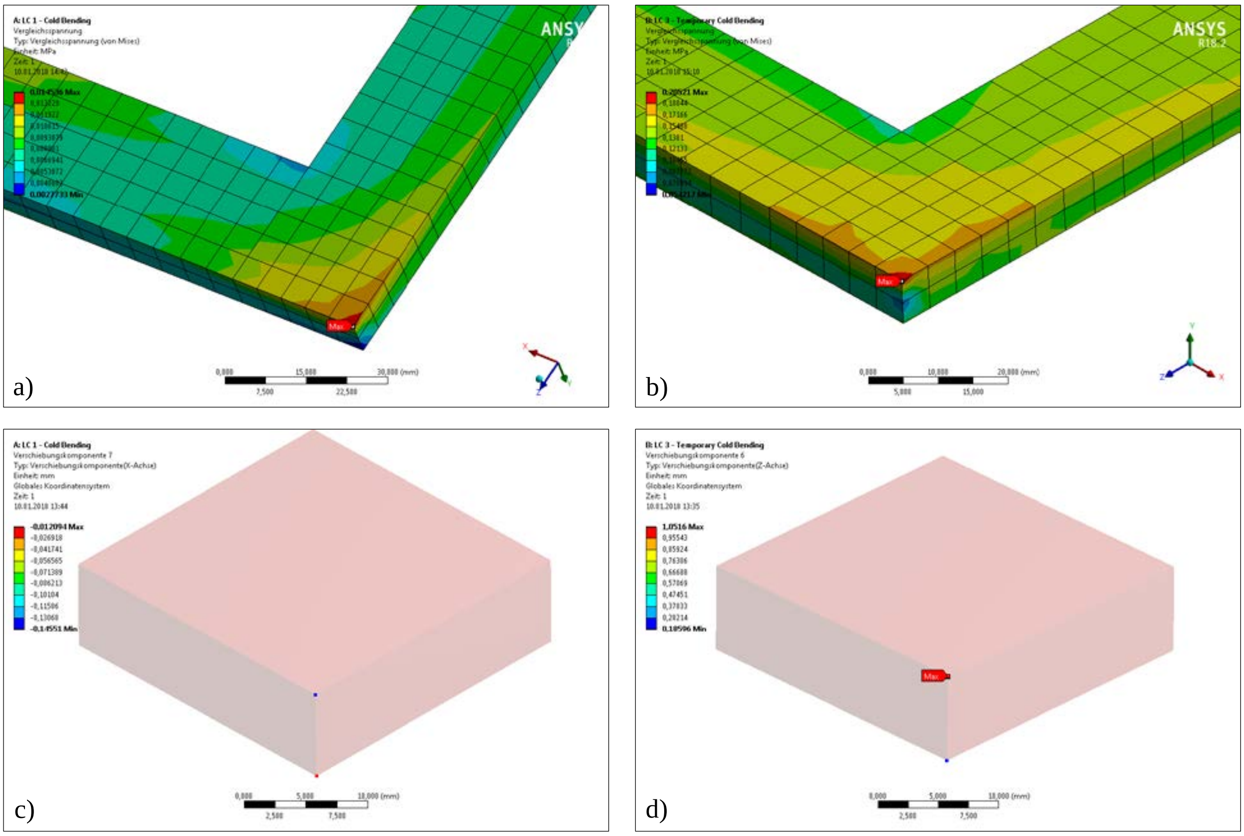


Fig. 12 Comparison between permanent cold bending (LC 1) and temporary state during installation (LC 3): equivalent stresses - a) LC 1 and b) LC 3, different shear deformation - c) LC 1 and d) LC 3

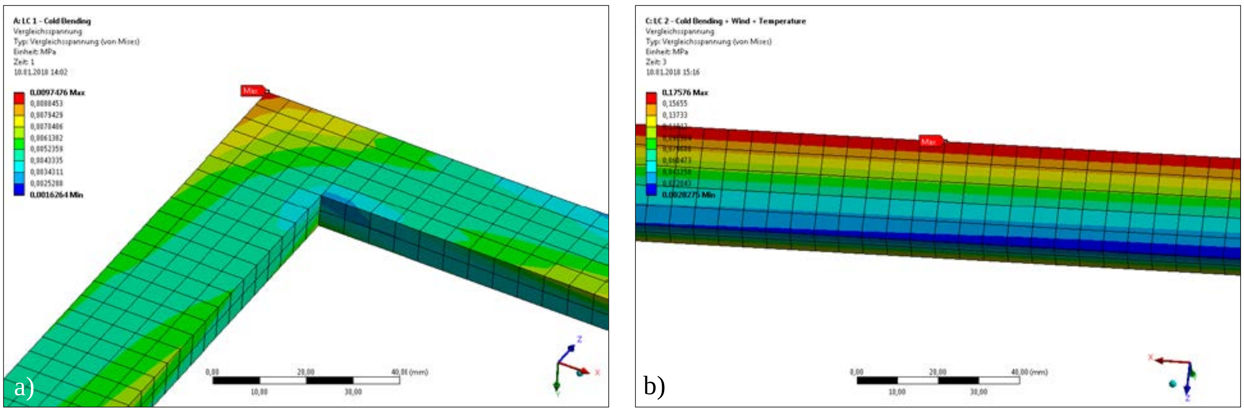


Fig. 13 Influence of stress relaxation on the equivalent stresses (von Mises) in the SG joint: a) LC 1 (cold bending) and b) LC 2 (cold bending + wind + temperature)

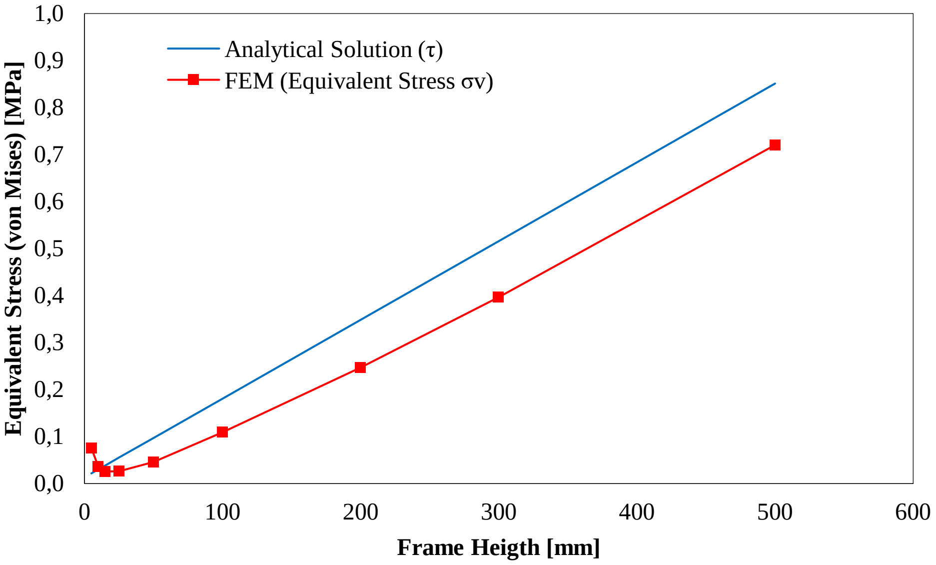


Fig. 14 Influence of the frame height on the resulting stress in the SG joint caused by cold bending for the geometry and forced deformation of the façade elements of Mistral Tower

5. Conclusions

The development of Mistral Tower in Izmir offers the chance to evaluate in detail the impact of different frame solutions in combinations with different production and installation methods on SSG joints of cold-bent façade elements.

Outside available standards and guidelines, analytical equations are presented to dimension the SG joints in cold-bent systems and to prove that the design of slim adapter frame represents a basic requirement to limit cold bending effects while minimizing production efforts. Valuable SG joint optimization results can be further achieved if bonding on either pre-shaped (hot-bent) frame or pre-shaped (cold-bent) frame/glass assembly is possible, or if cold-bending stress can be confined to a limited timeframe by a clever production method in controlled conditions.

Advanced finite element simulations are implemented to validate analytical results and to evaluate equation approach proposed. The numerical calculation results prove that the joint dimensions selected in Mistral Tower on the basis of the analytical equations are effectively exploited. Significant deviations between analytical and FEM results are observed for the differential shear deformations occurring between supporting frame and glass due to cold-bending. Nevertheless, the shear stresses determined by means of the analytical equations are in the same range of the equivalent stress (von Mises) determined by the finite element simulations. Furthermore, the analytically determined stresses are on the safe side.

FE simulation is used also to estimate the influence of stress relaxation on cold bending stress. With reference to the joint dimensions and boundary conditions of Mistral Tower facade, the analysis leads to a stress reduction of approx. 30%.

Effective cold-bending solutions cannot be uncoupled from new principles of system design, pre-manufacturing and installation; further investigation about influence of permanent strain on material strength and relaxation effects also implemented in FE analysis can further contribute in finalizing solutions that are even more efficient.

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