

Performance-based material selection and design for freeform building envelopes

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Summary

A leading architectural trend for building envelopes incorporates complex geometries and freeform facades. This paper addresses the concept system design for the glazed facade system for the Abdullah Financial District (KAFD) Metro Station in Riyadh, currently at scheme design stage, which makes full use of freeform facades. Through a state of the art review and by developing design concepts for the KAFD façade system, the fundamental design principles of current technologies used to construct complex envelopes are evaluated. The paper shows that existing technologies present key limitations in achieving the complexity required for the project. The paper outlines the benefits of using emerging technologies, such as fibre reinforced composite materials, largely adopted in the aerospace and marine industries and presents a better performing design solution based on these principles. The performance of this novel approach is assessed at conceptual design level.

Keywords: freeform, FRP-Panel, complex geometry

1 Introduction

A distinctive strand of modern architecture is the use of geometrical complexity in building envelopes. This approach calls into question the validity of conventional design solutions for building envelopes, which typically address each individual performance requirement in turn. This design approach typically leads to a succession of layers in the build-up of the envelope, where each layer addresses a particular performance requirement. The resulting building envelope systems often meet the required environmental and structural performance, but in a complex and costly manner. Digital and parametric analysis tools, recently introduced into the design process, enable the analysis of thermal and structural systems of higher complexity than was previously possible in the timescale of projects. The ability to accurately design more complex systems unlocks new design solutions, especially in the use of less conventional and higher performing materials.

These challenges and opportunities in free-form building envelopes are explored and discussed in context of a live project: the King Abdullah Financial District (KAFD) Metro Station in Riyadh.

The first part of this paper focuses on the façade design approach for the KAFD project, based on existing technologies used to achieve complex building forms. Four main technologies have been identified, together with representative built precedents. A final assessment on the merits of each technology is provided, which aims to identify the effectiveness of each design approach. The second part presents an innovative design approach using fibre-reinforced polymers (FRP) in order to overcome the limitations identified in existing technologies.

2 Design Approach of integrated facade concept for King Abdullah Financial District (KAFD) Metro Station

5.1 Description of façade systems concept and requirements

The planned King Abdullah Financial District (KAFD) Metro Station [Figure 1] is a live project within the Riyadh Transportation Strategy Plan. The design for the external envelope exhibits a complex geometry, combining different facade systems: Opaque areas clad in open jointed doubly curved panels (rainscreen on steel structure)

- (i) Glazed areas with external complex solar shading elements
- (ii) Glazed areas at ground level with external extruded aluminium shading louvers



Figure 1: External 3D view.

Figure 2: Close up: (a) one entire glazed "eye" (b) Steel diagrid

This paper focuses on the design of one glazed "eye" formed by the glazed area and the external solar shading elements [Figure 2 (a)]. Existing technologies and representative case studies have been evaluated [Table 1 to Table 3] in order to develop a suitable design approach for this system based on the following requirements:

- The façade has to follow a complex structural shape and provide a waterproofed and thermally insulated envelope around a structure, which is not driven by a structural primitive, which seeks to provide structural efficiency. The form is driven by the requirements to enclose the space with the minimum amount of internally air-conditioned volume. Consequently, the zones for the depth of the façade and its supporting structure are required to be minimised to contribute to this concept.
- The speed of installation of the façade systems, given the programme requirements of constructing a rapid transportation system,
- The durability of the façade materials given the extreme environmental conditions to which the building will be exposed.

5.2 Design development based on current technologies

Structural shells

The first approach considered is to achieve the complex geometry of each "eye" directly through the shape of the primary structure. The material used typically for this purpose is reinforced concrete. The main benefit of using concrete is that it can be cast into large-scale monolithic forms of any shape without joints in the material. Concrete can be either poured directly into formwork, or sprayed onto pre-mounted reinforcement, or delivered as pre-cast elements on site. For complex geometries, in-situ concrete is not efficient in terms of time and cost due to the preparation of the complex shaped formwork. Consequently, sprayed concrete is increasingly used for complex shapes, despite the fact that its inherent disadvantages of reduced durability and stiffness which results in a thicker cover and increased overall depth of the cast element.

The thermal insulation is set either within the concrete during pouring or alternatively is point-fixed on the internal or external face of the concrete. The waterproofing, normally liquid polymers or resin, is applied externally and can be coloured or transparent. The facade can be either left with a fair-faced concrete appearance or finished with decorative elements [1]. Another trend for opaque complex geometries is the use of a skeletal steel substructure onto which a façade a façade build-up is applied, comprising insulation, waterproofing and gypsum panels internally and cladding panels externally.

For the KAFD glazed system the major limitation of this opaque shell technology is the required number of perforations needed to meet the natural daylighting requirements, which would have led to a highly complex formwork if a concrete solution had been preferred Moreover, given the restriction of a steel primary structure [Figure 2], a concrete wall would exceed considerably the allowed superimposed dead load from the envelope. Consequently a façade solution using a supporting steel structure was developed.

Precedent	Location	Key features
The Selfridges Building	Birmingham	Free-form spraved concrete envelope coated with liquid plastic (waterproofing guaranteed for
	(2003)	35 years), covered with decorative elements.
Museo Soumaya	Mexico City	Primary steel structure provides support for the opaque façade mesh. Decorative aluminium
-	(2011)	cladding finishes the outer skin of the façade construction
Restaurant Los Manantiales	Xochimilco	Doubly-curved thin shell exposed concrete; thermal performance not a design parameter at that
	(1958)	time of construction.

Table 1: Structural shell: list of precedents.

Site-assembled modules

The facade system of the KAFD project has opaque and glazed areas, protected by shading elements [Figure 3]. A site-assembled approach lends itself to the combination of two existing technologies: the stick system and the rain screen system. The thermal insulation and waterproofing of the building are realised on site, whilst rain screen technology is used for the complex shading devices that define the external complex form of the façade. The first design approach draws from stick glazing technology. Stick systems are assembled on site by fixing infill panels to a loadbearing steel or aluminium subframe, which follows the complex geometry of the building. Individual opaque or glazed elements are set into place and attached to the carrier structure, including thermal breaks while assembling. This technology is adapted for rectilinear glazed curtain walls as well as for non-modular constructions and allows a high degree of freedom in its installation sequence. Methods of fixing are either toggle type, pressure plate or point fixing, sometimes with decorative caps [1]. The integrated, flexible silicone seal between the different panels can accommodate structural movement. This site-assembled construction approach leads to a layered construction addressing in turn each environmental and structural requirement. The site-assembled option would require the following build-up: marine grade plywood (or similar composite board substrate), vapour barrier, thermal insulation and waterproofing membrane on top, integrated into an aluminium sub-frame, which is fixed back to the diagrid steel structure [Figure 3]. Glazed elements are framed and also set into the aluminium sub-frame [1]. The fixing points of the external solar shading elements and internal GRG cladding panels penetrate the waterproofing and thermal line and need a special wet seal performed on site [Figure 3(b)]. A wet seal applied on site is also required to waterproof the interface between glazing panels and the aluminium sub-frame. A stick system is usually drained and ventilated at the outer surface. A ventilated zone behind the rubber based wet seal creates a pressure equalised chamber between outside and inside the system avoiding water to being drawn into the system. This chamber is also internally drained, providing a second layer of protection against moisture penetration. Due to its double level of protection, this technology can be used for overhead applications, where the action of gravity increases the risk of leaks and water can therefore be collected and drained in the internal chamber. The thermal insulation of stick systems is secured by providing a full thermal break through the structural profiles. Evaluating the KAFD facade, the complexity of the alternating glazing and opaque pattern results into a considerable number of interfaces, which require most components to be cut and assembled on site. This requires a continuous waterproofing membrane in order to ensure a continuous weatherproofing line and avoid risk of moisture penetration through the many interfaces. The use of continuous waterproofing membrane does not allow a clear strategy for accommodation of movements of the complex supporting structure at defined movement joints. This increases the risk of the membrane tearing at highly stressed locations during the service life of the building, leading to moisture penetration, which is both difficult to trace and to repair. This design approach relies on precise overlapping of waterproofing membranes and on-site wet sealing at several interfaces, presuming excellent workmanship to achieve the same quality that can be achieved with factoryassembled systems. Site-assembled systems are also likely to require scaffolding, which would inevitably slow down installation which is not compatible with the construction programme and the subsequent need to perform different operations in parallel on-site.

In order to overcome these obstacles, the use of pre-fabricated panels has been considered. Prefabricated panels can combine opaque and transparent elements. Each panel consists of a supporting aluminium frame, which provides the required structural stiffness for the infill panel, a substrate of marine plywood to support the thermal insulation (open or closed-cell) and a double-glazed unit already sealed to the supporting frame. The pre-fabricated panels are clamped together and fixed back independently to the primary structure [Figure 4]. The use of a continuous waterproofing membrane on top or wet-sealing of the interfaces (in case the individual panels are waterproofed already) is required to ensure a continuous waterproofing line of the build-up.

Both the application of wet-seals and the installation of a continuous waterproofing membrane would require high-level of workmanship on site and possibly scaffolding.

The waterproofing layer requires additional protection against UV radiation. This extra layer needs to accommodate the complex outer geometry, to provide the required shading and must be easily replaceable. The solution considered to meet these requirements is the application of the rainscreen principle. Rainscreens are cladding elements that are mechanically fixed to the primary structure. A rainscreen protects the waterproofing membrane, reducing the combined effect of wind and rain by creating an air-barrier between the facade surface and the waterproofing layer. Providing an air gap between façade structure and the water-repellent line allows the circulation of air on the moisture barrier and reduces the risk of trapping water and humidity within the facade system [1]. Complex fixing brackets can be used to provide adjustability in three directions and accommodate complex geometries, such as doubly curved surfaces, independently from the supporting substructure whilst simultaneously accommodating structural movements. The architectural intent and environmental conditions of the KAFD project demand a material that can be moulded into complex shapes and exhibits a high durability of the material, in terms of resistance against corrosion, UV radiation and fire. Composite materials are suitable to meet these requirements.



Figure 3: 1st design approach: on-site stick elements & rain screen (a) exploded view (b) cross-section detail.



Figure 4: 2nd design approach: on-site stick pre-fabricated elements & rainscreen (a) exploded view (b) cross-section detail.

For both site-assembled and the pre-fabricated systems the shading elements are installed after the waterproofing is applied and therefore require additional workmanship on site. This requirement can be resolved with the use of a unitised technology.

Precedent	Location	Key features
Site assembled modules		
British museum	London (2000)	On-site welded steel substructure (process results in minimal tolerances), acting as support for framed, triangulated glazing, which differs in size in order to take up the geometry
Terminal 3, Bao'an International Airport	Shenzhen (2013)	Double-skin facade using three different layers of supporting steel frame; fulfilment of requirements & assembling with consecutive layers
Myzeil Shopping Centre	Frankfurt (2009)	The stick shells geometry was made with grids of pre-fabricated six-beam nodes with edge- clamped glazing and beams welded on-site.
Dali museum	St. Petersburg (2011)	Double-node technology solves free form geometric issues of beam twist with aluminium edge-clamped glazing.
The Canopy at the Smithsonian Institution's Kogod courtyard	Washington D.C. (2008)	Aluminium framed, flat glass elements fixed to U-profiles attached to steel sub-frame. Dome- shaped glazed roof allows drainage through U-profiles and final drainage through pillars
Dalian International Conference Centre	Dalian (2013)	Stick glazing with aluminium outer rain screen or metal louvers on top is supported by a structural steel mesh.
Prada Aoyama	Tokyo (2003)	Toggle-fixed, silicone sealed glazing elements with partly double curved glass; attached back to a diagrid-shaped steel frame.
CET Budapest by ONL	Budapest (2010)	Complex curved shaped achieved with alternating toggle-fixed glazing and opaque facade elements fixed to the structural steel.
Park House	London (2012)	Semi-unitised System: prefabricated fixing frame, acting as mullion with toggle fixed glazing and opaque elements
King Abdulaziz Centre	Dhahran (expected 2015)	Semi-unitised System: the stick glazing provides the waterproofing and thermal line; external shading consists of pre-fabricated stainless steel tubes, attached to adjustable brackets.
Rainscreen		
Georges-Frêches School	Montpellier (2012)	Cast in-place and free-form sprayed concrete envelope with complex-shape aluminium rain screen.
Guggenheim Museum	Bilbao (1997)	Titanium rain screen combined with stone cladding and glazed areas; self-healing membrane

Table 2: Side assembled modules & rain screen: list of precedents.

Unitised technology

The use of pre-fabricated components leads to the development of the system into a fully unitised system based on the principle of fixing each panel independently to the primary structure by rapid installation on site. This approach accommodates the movements of the panels and the structure in the joints between panels, specially designed to provide a watertight interface. The possibility of fixing the panels directly with the shading elements incorporated without requiring any additional waterproofing applied on site allows the installation to be accelerated and provides a high level of quality control during manufacturing. The system can also be structurally designed to a higher degree of precision to accommodate engineered seals between panels. Typically, glazed unitised panels are set side by side, floor by floor, restrained on one end and fixed on the other. Panels are secured by brackets fixed to a steel frame, which is then is attached to the primary structure [1]. The movements are accommodated in the joints between panels. The frame of each unitised panel is usually aluminium. The gaps between each panel are sealed with synthetic rubber gaskets. The waterproofing is generally fixed to the panel before installation and works when panels are slotted into place. The outer line of defence is provided by rubber-based baffles set on each panel so that they press together to form a seal. An aluminium drip can be added to the outside as a first wind barrier, but allowing water to drip out again behind this profile. Any rainwater penetrating the profile is stopped in a pressure-equalised chamber that prevents water getting any further and is drained out again. The main advantages of unitised systems in construction are the speed of installation and the level of quality control possible within controlled workshop conditions. Unitised panels are particularly popular in vertical façades of high-rise buildings. Non-vertical applications are possible, but they require significant adjustments to accommodate the new waterproofing conditions.

Given the system requirements for the KAFD Metro, particularly the need for fast installation, the application of unitised technology is particularly appealing. Figure 5 shows the assembly sequence of four unitised panels fixed onto the supporting diagrid structure. Each panel consists of a steel frame with a glazed unit and sizes approx. $2 \times 2 m$. Panels are fixed independently to the steel diagrid. The main limitations of this unitised approach is the waterproofing of the system on the inclined doubly-curved surface. The draining technology is based on water being able to drain within the framing elements; for this reason the conventional system is ill-suited to overhead and inclined applications. Only minimal inclinations (usually up to $10^{\circ}-15^{\circ}$) are allowed to avoid risk of leakage. Thermal

breaks set into the frame reduce thermal bridging through the frame. Overall, the solution presented [Figure 5] cannot respond to the geometry requirements without modification.



Figure 5: 3th Design Approach: assembly of unitised system; (a) exploited view (b) cross-section detail.

Table 3:	Unitised	technology:	list of	precedents.
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Precedent	Location	Key features
62 Buckingham Gate	London	Unitised curtain wall divided into 11 facets, each exhibiting a different inward and outward
	(2013)	inclined angle (between -5° to 10°) for the glazing.
30 St Mary Axe - Gherkin	London	Unitised system for small inclinations combined with stick system for large inclinations located
	(2004)	at the top of the building

3 Comparison of precedents

The Table 4 shows the comparison of the selected representative precedents for each technology against the same parameters in order to gain a general overview about the performance achieved by each technology when applied to real projects. The main benefits and drawbacks of each design approach are evaluated in terms of the ease of the construction sequence, the integration of facade layers, the general facade design time and post-construction durability issues.

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Cano Instit	py at ution	Smithsonian 's courtyard	3+4	II	0	0	+			
Dalia	n Int	. Conf. Centre	3	Ι	-	-	0			
Prada	а Аоу	ama	3	V*	0	0	-			
CET	Buda	pest by ONL	3	II	0	0	0		🗡 Initia	al leaking
Park	Hous	se	3	I+V	0	0	0			
King	Abdı	ılaziz Centre	1	Ι	-	-	+			
Georg	ges-F	rêches School	1	Ι	-	-	-			
Gugg	enhe	im Museum	2+3	Ι	-	-	0			
62 Bu	ckin	gham Gate	4	V	+	0	+			
30 St	Mar	y Axe Gherkin	3+4	II	+	0	+			
Trimo	1	Structural shell, opaque	Com	plexity I	Doubly curved en	velope; curved elemen	its	Evolution	-	Low
Type	2	Rainscreen	of ge	ometry II	Doubly curved en	velope; flat elements		notation	0	Medium
	3	Site assembled envelope		III	Singly curved env	elope; curved element	s		+	High
	4	Unitised technology		IV	Singly curved env	elope; flat elements				-
				V	Flat envelope; var	iable inclination possil	ble			

* integrates flat and doubly curved elements

From the evaluation of the initial design proposals and the corresponding precedents, it can be observed that current technologies, originally conceived for more straightforward buildings, are often used in the construction of geometrically complex buildings. However, none of these technologies was specifically developed for complex geometries. From the above review and comparison of precedents, the following remarks can be made:

- Using site-assembled modules for complex opaque and glazing pattern difficulties in defining a clear structural strategy to accommodate structural movement. At the same time it relies on high quality of workmanship on site, which leads to a high risk of leakage post construction. Installation often requires the use of scaffolding and is time-intensive.
- Prefabricated modules increase the level of manufacturing and control of quality within the workshop and ensure faster installation. Panels are clamped on site, require an additional waterproofing finish, either using a waterproofing membrane or wet-sealing the interfaces. The shading panels are installed after the waterproofing. This still relies on a skilled workmanship on site and potential use of scaffolding. Given the limitations in panel size due to its self-weight, the large number of joints or interfaces presents an elevated risk of leakage.
- Unitised panels offer substantial advantages in terms of installation speed and movement accommodation, but cannot respond easily to complex geometries, given the high risk of leakage on inclined surfaces.

4 Composite materials

The use of emerging technologies and materials allows a re-think of the design strategy for the KAFD Metro, starting from a more radical approach that aims to achieve a complex envelope on a light-weight supporting structure.

The key parameters for this design approach are as follows:

- Maximise span of the modules to reduce number of joints
- Minimise weight of modules in order to minimise loads and resulting movements on the lightweight supporting structure. This also facilitates maintenance and replacement of components.
- Predicable behaviour of the system in terms of accommodation of structural movements.
- Reduce on-site operations to maximise speed of installation, whilst avoiding scaffolding around complex shapes.

The limiting factor in achieving larger spans is the use of infill panels set into spanning framing elements. More efficient structural materials would allow the use of panels as load bearing, self-spanning shell structures. This is commonly achieved by composites in transportation and other industries, but these are still novel materials in the construction industry, where the design is not only driven by structural efficiency but is largely restricted by the need for longer term durability. The main advantage of composites is their ability to provide an integrated and light-weight structural solution for complex shapes. Furthermore, composites can be engineered to be highly durable to achieve high design life requirements and the recent development of fire retardant epoxy resins ensures an appropriate fire rating.

FRP Sandwich elements

Fibre-reinforced polymers (FRP) are able to meet a full range of structural, environmental and geometrical facade performance requirements integrated within one layer [2]. It is a lightweight composite material, exhibiting a high tensile strength. FRP consists of liquid resin containing fibres such as glass, carbon or aramid, all exceeding the ultimate tensile strength of steel in several orders of magnitude. The thermal expansion is a function of the fibre content and is higher than the values for concrete, glass and steel, but similar to aluminium and wood [3]. FRP can achieve excellent fire- and corrosion resistant and weather-tightness properties, which allow a long-term external use of the material [2]. Stiffening of the material is either obtained with a thicker and therefore costly lay-up or by a structural composition of different elements and/or shapes [3]. In the construction industry FRP Sandwich panels with foam core have a wide application range, because the integrated thermal insulation cuts down significantly the workmanship on site. A panel consists of two FRP outer skins

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and a structural foam core, which incorporates a higher shear resistance as well as the insulation layer. The final resin coating protects the fibre and polyester lay-up from moisture. The structural advantages of a sandwich panel are the high stiffness-to-weight ratio allowing spans and the good fatigue strength. Additionally, a very good thermal insulation and acoustical absorption can be achieved [2]. As it is a moulded material any shape can be manufactured using prefabricated moulds. The recently developed vacuum assisted infusion moulding method allows the creation of high performance units with the potential to meet load-bearing application. As the KAFD façade requires large, lightweight panels in order to reduce the amount of panel connections, a lightweight and extremely stiff fibre material, such as carbon, is chosen.

Table 5. FRP composites: list of precedents	Table 5:	FRP	composites:	list of	precedents.
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Precedent	Location	Key features
PCT Prototype RAK Gateway	(in process)	FRP façade panel integrates outer skin requirements
The Eyecatcher building	Basel	Primary structure and façade elements consist of GFRP
	(1997)	
Enexis Building	Zwolle	Facade panels made out of FRP (13x3 m)
	(2013)	

4.1 Conceptual design evaluation

The final design approach is based on a CFRP sandwich panel, acting as a structural element, which incorporates different components, such as insulation, water proofed skin, structurally bonded glazing elements and cast-in anchors used as fixing points for the inner and outer cladding panels; without creating thermal bridges or major conflicts with the waterproofing membrane. Carbon fibres provide the stiffest panels and are therefore preferred to aramid or glass fibres. The set-up of the CFRP panel enables the combination of 4 panels into one; the potential size of 4 m x 4 m is shown in Figure 6. CFRP is a high performance material, which easily can withstand point loads, e.g. via bolts. Cast-in threaded inserts allow the CFRP panel to be fixed back to the primary structure using a simple bolt connection. Spider brackets as connecting point to the primary structure enable the simple adjustment of structural differences and reduce bending on the supporting structure by acting on the structural nodes of the diagrid to transfer facade loads. Each panel can be independently fixed to control movements at the joints. Due to its high stiffness-to-weight ratio spans of up to 10 m can be achieved. The initial panel size of approx. 2 m by 2 m is no longer a restriction; shape and size of the panels are only limited by transportation constraints. The larger spans of CFRP panels also allows a further simplification of the inner structural metal-grid and leads to considerable steel savings. The integrated insulation and the high performance fibres made of carbon fibre enable an overall component thickness of only 120 mm, exhibiting a high strength [Figure 6].



Figure 6: Build-up optimized design approach using CFRP; (a) exploited view (b) cross-section detail.

CFRP panels can be connected in various ways. The conventional method consists of clamped fixing using pressure plates, which simplifies the connection complexity. The panels are clamped together on-site and the clamps allow for internal drainage and therefore their use for inclined applications.

Gluing is also being explored as a technical solution for the joints. This would allow structural continuity to be achieved between panels, potentially even further savings on the supporting diagrid structure and faster installation [Figure 7].



Figure 7: possible panel sizes for glued connection

The main benefits of adapting the CFRP option are the significant reduction in self-weight of the façade and simpler waterproofing.

Nevertheless designing with CFRP is complex as it is not a conventional material in the construction industry and the design process needs to be assisted by analytical and experimental validations. For the preliminary structural and thermal analysis a panel of the size 4 m by 4 m is evaluated. This panel represents the merging of four 2 m by 2 m elements used in the original design [Figure 8].



Table 6: Build- up and material properties [4].

Figure 8: CFRP Panel FE model and Loads.

The numerical model of the FRP panel has been developed with Sofstik 2014 [Figure 8]. QUAD elements are used; the model is defined as a shell, where the material properties are assigned to the The build-up and the material chosen surfaces. properties are shown in Table $\mathbf{6}$. The boundary conditions comply with a statically determinate system. The analysis was carried out for SLS and ULS respectively. The maximum principal stresses are 48.8 MPa on the top site and -46.7 MPa on the bottom site of the panel [Fehler! Verweisquelle konnte nicht gefunden werden.]. The panel thickness of 125.7 mm reaches a maximum deflection of 11 mm over a span of 4 m [Fehler! Verweisquelle konnte nicht gefunden werden.]; the deflection is within the critical limitation of 20 mm given by the span over 200. The stress distribution across the thickness was also determined. It was found that the limiting parameter is the deflection, as the stresses throughout the different layers range several orders of magnitude below the equivalent resistance strength $(\sigma_{max,2^{nd}layer} = 94 MPa \le 1111 MPa = \sigma_{r,2^{nd}layer})$. The preliminary conservative evaluation of the shear stresses shows, that the foam core is able the resist the maximum shear forces ($\tau_{max,foam} =$ $0.8 MPa \le 1.2 MPa = \tau_{r,foam}$ without taking the outer carbon fibre sheets into account. The stress contour and deflection plots are not shown here for brevity.

The preliminarily thermal analysis was undertaken with the software flixo pro 7.0. The thermal analysis has been performed according the BS Eurocode [5]. In accordance with the standard BS EN ISO 10077:2012 the external temperature is 0 °C and internal temperature 20 °C. In order to evaluate the improvement in thermal performance the design approach based on the FRP Panel is compared with the semi-unitised approach using prefabricated panels and on site assembling. The same cross-

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section is considered. It represents the worst-case scenario including the fixing elements for the external and the internal cladding. The system using carbon fibres presents higher thermal performance. An overall reduction in the heat flux [W/m] of 25 % is achieved as well higher surface temperatures, reducing the risk of superficial condensation [Figure 9].



Figure 9: thermal analysis of prefabricated panel (left) and FRP Sandwich element (right).

4.2 Future work

To verify the mechanical properties of the CFRP panels it must be subjected to (destructive) tests in order to evaluate [6]:

- Delamination strength of the laminate/ bonding strength between core and laminate
- Tensile and bending strength (4PB test) of the laminate/ shear strength of the core
- The connection methods used between CFRP panels and between CFRP panels and the primary structure need to be developed and require experimental validation.

Furthermore, the fibre content across the panel can be optimized to suit the stress distribution and deflection. Possible combinations of integrating the rainscreen as structural element of the façade panel will be explored.

5 Acknowledgements

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