Accepted Manuscript

Structural characterisation of adaptive facades in Europe - Part II: Validity of conventional experimental testing methods and key issues

Chiara Bedon, Dániel Honfi, Klára V. Machalická, Martina Eliášová, Miroslav Vokáč, Marcin Kozłowski, Thomas Wüest, Filipe Santos, Natalie Williams Portal

PII: S2352-7102(19)30037-3

DOI: https://doi.org/10.1016/j.jobe.2019.100797

Article Number: 100797

Reference: JOBE 100797

To appear in: *Journal of Building Engineering*

Received Date: 8 January 2019

Revised Date: 4 May 2019

Accepted Date: 5 May 2019

Please cite this article as: C. Bedon, Dá. Honfi, Klá.V. Machalická, M. Eliášová, M. Vokáč, M. Kozłowski, T. Wüest, F. Santos, N.W. Portal, Structural characterisation of adaptive facades in Europe - Part II: Validity of conventional experimental testing methods and key issues, *Journal of Building Engineering* (2019), doi: https://doi.org/10.1016/j.jobe.2019.100797.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

ACCEPTED MANUSCRIPT

Structural characterisation of adaptive facades in Europe - Part II: validity of conventional experimental testing methods and key issues

Chiara Bedon[1*], Dániel Honfi[2], Klára V. Machalická[3], Martina Eliášová[4], Miroslav Vokáč[5], Marcin Kozłowski[6,7], Thomas Wüest[8], Filipe Santos[9], Natalie Williams Portal[10]

Abstract

Given their intrinsic features, adaptive facades are required to strictly satisfy rigid structural performances, in addition to typical insulation, thermal and energy requirements. These include a minimum of safety and serviceability levels under ordinary design loads, durability, robustness, fire resistance, capacity to sustain severe seismic events or other natural hazards, etc. The overall design process of adaptive facades may include further challenges and uncertainties especially in the case of complex assemblies, where even multiple combinations of material-related phenomena, kinematic effects, geometrical and mechanical characteristics could take place. In this context, experimental testing at the component and / or at the full-scale assembly level has a fundamental role, to prove that all the expected performance parameters are properly fulfilled.

---

[1] Department of Engineering and Architecture, University of Trieste, Trieste, Italy.

(*)= corresponding author. Email: chiara.bedon@dia.units.it, phone: +39 040 558 3837, office: University of Trieste, Department of Engineering and Architecture, Piazzale Europa 1 (building C9), 34127 Trieste, Italy

[2] RISE - Research Institutes of Sweden, Gothenburg, Sweden

[3] Klokner Institute, Czech Technical University in Prague, Prague, Czech Republic

[4] Faculty of Civil Engineering, Czech Technical University in Prague, Prague, Czech Republic

[5] Klokner Institute, Czech Technical University in Prague, Prague, Czech Republic

[6] Faculty of Civil Engineering, Silesian University of Technology, Gliwice, Poland

[7] Faculty of Engineering, Lund University, Lund, Sweden

[8] Institute of Civil Engineering, Lucerne University of Applied Sciences and Arts, Lucerne, Switzerland

[9] Department of Civil Engineering, New University Lisbon, Lisbon, Portugal

[10] RISE - Research Institutes of Sweden, Gothenburg, Sweden

Several standards and guideline documents are available in the literature, and provide recommendations and procedures in support of conventional testing approaches for the certification and performance assessment of facades. These documents, however, are specifically focused on ordinary, static envelopes, and no provisions are given for the experimental testing of dynamic, adaptive skins. In this regard, it is hence expected that a minimum of conventional experimental procedures may be directly extended from static to dynamic facades. However, the validity of standardized procedures for adaptive skins is still an open issue. Novel and specific experimental approaches are then necessarily required, to assess the structural characteristics of adaptive facades, depending on their properties and on the design detailing.

In this paper, existing fundamental standards for testing traditional facades are first recalled and commented. Special care is spent for the validity and reliability of conventional testing methods for innovative, adaptive envelopes, including a discussion on selected experimental methods for facade components and systems. Non-conventional testing procedures which may be useful for adaptive skins are then also discussed in the paper, as resulting from the research efforts of the European COST Action TU1403 'Adaptive facades network' - 'Structural' Task Group.

Keywords: adaptive facades, structural performance parameters, metrics, experimental testing, experimental facilities, testing methods

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

1. Introduction

Next generation of building enclosures are complex adaptive systems combining high-tech components and latest technology achievements. This might involve the use of smart materials and kinematic mechanisms, which make them able to respond to transient loading and boundary conditions in order to improve the overall building performance (see for example [1-3]). Although current numerical tools allow for extensive investigation of the structural performance of adaptive facades at different levels, as also discussed in [1], the ultimate verification of performance criteria required by building regulations and standards might involve dedicated experimental testing procedures.

The performance of a building’s facade greatly determines the satisfaction of occupants, with regard to perceived serviceability and some extent safety in operational conditions (see [4-6], etc.). The basic requirements of a given facade, in this context, cover different aspects that should be properly combined, being mostly related to airtightness, water-permeability, fire resistance and overall structural performance [7, 8].

Given such a final goal, the existing standards and guideline documents for testing facades specify a set of minimum performance requirements to satisfy, with detailed provisions for systems tested in laboratory conditions or outdoor environment, respectively. The purpose of testing could be to prove the fulfilment of specific preconditions, but also to prove the compliance with some strict requirements, thereby highlighting superior performance of the tested facade. Testing of facades might be also requested by the end user (i.e., builder, consulting engineer, etc.), or by an approving authority (i.e., a local or state government body).

The performance assessment of a given facade as a whole, in this regard, can be carried out in an experimental facility or on site, after installation. During laboratory testing, a mock-up is built mimicking a certain part of the facade (i.e., using the same materials and dimensions as to be constructed in the real project). The exposures applied at mock-up testing usually represent extreme loading conditions, that during the building lifetime could lead the system to failure. Testing on site, on the other hand, typically focuses on the identification of spots with insufficient performance, due to fabrication and/or installation errors. The

ACCEPTED MANUSCRIPT

exposure levels are typically lower than mock-up testing. For adaptive facades, this approach includes the check of proper functionality, for all the adaptive features.

In both the cases, the testing configuration should include all the relevant details for the required performance assessment, thus a certain flexibility in conventional methods and procedures may be expected for innovative skins. For example, during experimental testing of the watertightness of a given facade, the specimen should properly include joints, corners and all the assembly details that could be relevant. A specific range of static and / or cyclic water pressures is typically of interest to assess the ability of the facade to avoid water penetrating the building, due to i.e. heavy precipitation. Joint detailing is relevant also for structural performance assessment of the same facade, but the key boundary/loading configuration of interest should be properly detected, case by case.

The structural performance is in fact commonly associated to the resistance assessment of cladding elements and connections to the super-structure, against wind loads. However, especially for adaptive facades, more other issues might also be relevant. The reference wind pressure for design and testing, in this regard, mainly dependent on the geographical location of the system, but also on the dimensions and on the shape of the full building. Cladding elements need not only withstand wind loads, but also stay in place with limited deformations, and possibly null damage. The reliable determination of the limit deformations for adaptive facades – given the possible presence of moving and/or flexible components – might not be obvious, and in counterpart could represent a limit of the expected adaptive performances, or in any case be difficult to satisfy.

As far as the airtightness is taken into account, the expected air leakage through the facade (i.e., of primary interest for energy efficiency and acoustics) must be properly measured, as a function of a given static pressure. The volume of air leak is then compared with the allowable volume, which is generally provided by standards for conventional claddings. Fire resistance testing, in addition, is carried out using full scale mock-ups and typically focuses on reaction to fire of materials and fire spread in the facade system. Impact and blast load scenarios, finally, should be properly addressed, via test setup configurations able to capture

ACCEPTED MANUSCRIPT

the expected structural dynamics of a given system, at the assembly but also at the component and material levels.

This paper follows and extends the discussion reported in [1], with a specific focus on experimental testing issues. The document, in particular, first collects some key standard provisions for conventional testing the performance of conventional facades, with a discussion of adaptive skins (Sections 2 and 3). In addition to standardized testing methods in use for static facades, a selection of experimental approaches is then proposed in Section 4, for some key facade components / loading conditions of primary interest for adaptive systems. As far as the structural performance of dynamic facades must be satisfied under a variability of multiple parameters (including variations in materials, boundaries, loads, activation systems, etc.), careful consideration and even unconventional testing approaches may be required, depending on the actual case. Finally, Section 5 briefly emphasizes the role of certified facilities for adaptive facades.

2. Relevant standards for the experimental assessment of facades

2.1 Available standards for conventional facades

When conventional facades needs to be experimentally assessed, standardized approaches are available to investigate their key performances regarding protection of the occupants, namely insulation to external conditions, on one side, and structural safety and efficiency, on the other side.

Within the European Economic area (EEA), all the products with a CE marking have a proved conformity with the relevant EU standards. Moreover, this allows free movement and sale of those products within the EEA, regardless of where they are manufactured. The most relevant standard for facades (with a specific focus on the typology of curtain walls) is certainly the EN 13830 ‘Curtain walling - Product standard’, see [9] and Section 2.2. Another relevant document is ETAG 034 ‘Guideline for European Technical Approval of Kits for External Wall Claddings’ [10], issued by European Organisation for Technical Approvals (EOTA). ETAG documents are issued and applied when product standards do not cover some specific areas. In addition to specific standards for facades, they have to also fulfil general harmonized requirements for

ACCEPTED MANUSCRIPT

construction products in Europe including mechanical resistance and stability, safety in case of fire, hygiene, health, protection against noise, energy and sustainable use of natural resources [11].

The EN 13830, more in detail, specifies different sub-tests and procedures for a facade performance classification by experimental testing. The main test procedure according to EN 13830 includes air permeability, watertightness (static conditions), wind load serviceability / resistance, air permeability, water vapour permeability, thermal transmittance, airborne sound insulation (see a selected example in Figure 1(a)).

(a)

ACCEPTED MANUSCRIPT

Pre-test *Detonation* *Post-test*

(b)

Figure 1. Example of experiments on conventional facades: (a) dynamic water penetration test (figure reproduced with permission from [12]) and (b) blast arena testing (reproduced from [13]).

ACCEPTED MANUSCRIPT

The reference experimental procedure has to be performed in one run, for the facade classification. The basic assumption is that the facade performance is addressed in reliable operational conditions, rather in an ideal laboratory setup. Moreover, the real scale test element often includes all the typical installation tolerances. Conventional test methods according to EN 13830 regulations are summarized in Table 1.

For adaptive facades, however, the actual relation (and hence the possible interference) between separate testing methods in use for curtain walls still needs to be assessed.

Adaptive facades might in fact change material properties, surface conditions, shapes and forms, local or global structural characteristics or other relevant features as a reaction to external phenomena (see also [1]). Therefore, also the expected performance of dynamic claddings (i.e., in terms of deflection, air tightness, water permeability, etc.) could modify within a specific scenario, and possibly do not fulfil the conventional requests of standardized test procedures. In accordance with Figure 2 and [18], different intrinsic adaptive features for a given skin can influence one or more test parameters. The figure indicates possible interactions between adaptive features and relevant key performance parameters. It is also clear that an adaptive material, component or assembly - depending on the specific properties and behavioural trends - could have different classifications, for each one of the adaptive states of the overall performance.

Table 1. Test methods for curtain walls, based on EN 13830 regulations.

Test method	Reference standard
Air permeability	EN 12153 [14]
Resistance to wind load	EN 12179 [15]
Watertightness	EN 12155 [16]
EN 13050 dynamic	EN 1027 [17]

ACCEPTED MANUSCRIPT

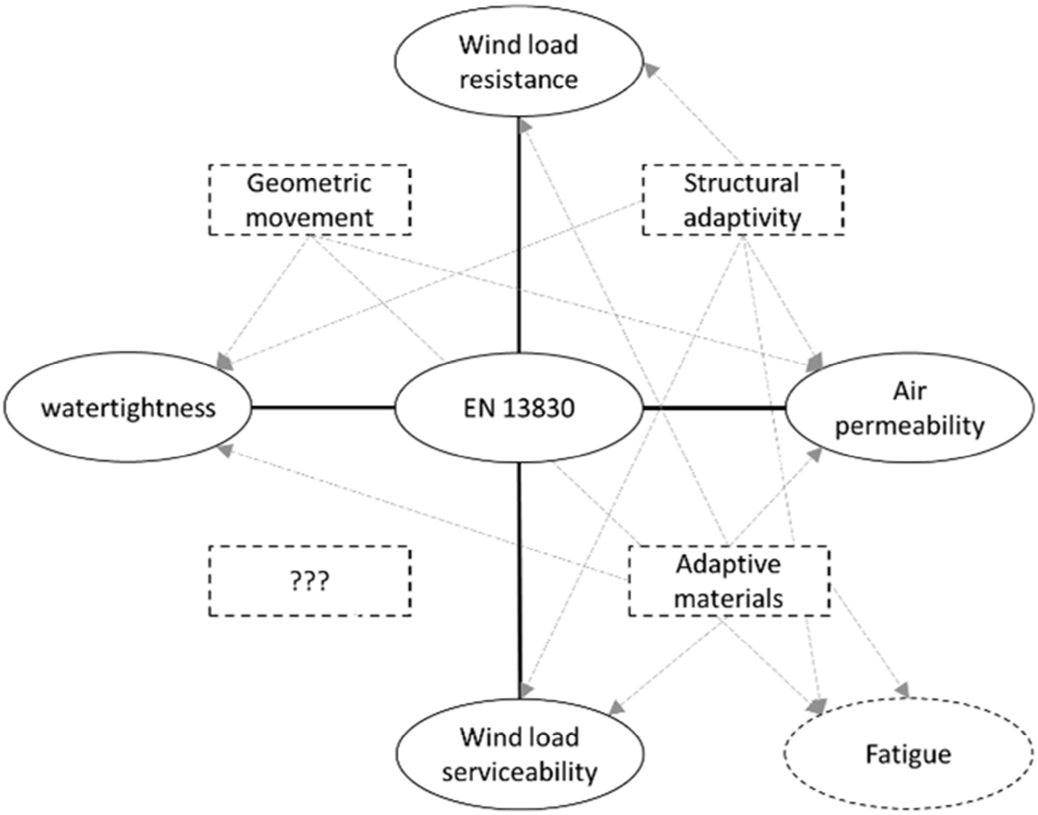


Figure 2. Influence diagram for testing adaptive facades, in accordance with existing EN 13830 regulations for curtain walls (reproduced from [18]).

An additional challenge arises when further key performance parameters for facades (i.e., thermal shock resistance, seismic resistance, watertightness under dynamic conditions, blast resistance (see for example Figure 1(b)), etc.) may be required for specific systems, even if not included in the base reference procedure for certification.

ETAG 034, for example, states requirements accompanied by corresponding test methods in fields of mechanical resistance and stability, safety in case of fire, hygiene, health and environment, safety in use, protection against noise, energy economy and heat retention, aspects of durability and serviceability.

From the point of view of the structure’s reliability, the ETAG 034 regulation document defines a number of mechanical tests of claddings. There is also a method prescribed for evaluating test results in order to obtain

ACCEPTED MANUSCRIPT

characteristic value for structural design, i.e., breaking force. This method is in accordance with EN 1990 where principles for design based on experiments are given too. The characteristic value is defined as an estimation of 5% quantile (with 75% confidence) and its value is also dependent on the number of available results and the standard deviation. Therefore, experimental determination of the characteristic value may lead to a relatively large number of testing specimens in some cases. Both normal and lognormal distributions can be used. The design value based on testing is equal to the characteristic value divided by the partial safety factor of given material. These principles shall be met even in the case of adaptable facades.

It is certainly clear that these standards and procedures are specifically developed for conventional, static facades. On the other hand, the definition of reliable standard testing procedures for a facade that can be intended as an adaptive, moveable, dynamic, kinetic, responsive, switchable, interactive, etc., system, is neither feasible nor promising. Therefore, the applicability of standardized testing approaches and the reference loading / boundary conditions to assess must be necessarily examined case-by-case. In addition, any possible negative correlation between a certain adaptive behaviour and several performance criteria should be also taken into account. For example, if a facade changes the form due to wind load, it is possible that joints could offer lower air permeability or water-tightness, hence requiring careful attention for assessment purposes. Additional special care, in this regard, should be spent for dynamic adaptive systems under extreme loads, including both accidental events, human-induced extreme loads, natural hazards, etc.

2.2 Feasibility of standardized tests for the assessment of adaptive facades

To achieve the CE marking and based on the existing regulations, a given curtain wall must conventionally fulfil the EN 13830 test procedure. The recommended testing methods are specifically dedicated to curtain walls kit that – in the form of building envelopes – are not expected to contribute to the load-bearing or stability of the main building structures, and could be replaced independently, when required. The reference test sample, in this regard, should be representative for the chosen product family, assumed that this sample contains the less favourable combination of features. The standard test ‘procedure A’ is as follows: air

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

tightness test, water tightness test, serviceability wind load, air tightness test, water tightness test, ultimate wind load. The ‘procedure B’ has an additionally test cycle for earthquake resistance.

Testing of adaptive facades is, in some simple cases, feasible with this standard. Facades with windows, doors or shading devices can be seen as adaptive. However, in the case of external shading devices (as slat blinds or fabric blinds) they are not an explicit part of the curtain wall testing and underlie EN 1932 [19] and others. Technically, the reason might be that conventional external blinds do not affect the facade performance. However, due to the representability of the test sample, external blind casings should be mounted and are passively part of the tightness testing. For windows and doors, there is another relevant product standard, namely the EN 14351-1 standard [20]. Thus, facades with openable windows / doors can be considered as simple adaptive facades which underlie two air tightness standards. Therefore, the test procedure for air tightness is considered as follows:

1) Measurement of facility air leakage Q_c (facade sample fully sealed);
2) Facade leakage measurement Q_{fc} (openable joints still sealed);
3) Measurement of total leakage, after that openable elements have been opened for five times Q_{tc}.

This gives the leakage for the facade Q_f (EN 12153 [14]) and for the window / door Q_j (EN1026 [21]) respectively, where:

$$Q_f = Q_{fc} - Q_c \qquad (1)$$

$$Q_j = Q_{tc} - Q_{fc} \qquad (2)$$

and Q_c, Q_{tc}, Q_{fc} are defined above.

These are two simple examples of adaptive facades tested according EN 13830. Undoubtedly, this is not what we typically consider as adaptive facades, on the other hand, it gives a hint how to handle adaptive facades when a CE marking is required. The thoughts previously summarised, in particular, should be taken into account when adaptive facade testing is carried out. As the current example shows, there are two ways to deal with adaptive features in testing, namely: (a) neglect it if no mutual influence is anticipated, or (b) the

ACCEPTED MANUSCRIPT

performance is covered by other standards. However, possible negative interactions should be properly investigated, since not covered by standards and, if needed, additional tests should be performed.

3. Testing the structural performance of adaptive facade systems

3.1 Experimental testing during system development

The evaluation of the structural performance when developing an adaptive facade concept is a complex task, since due to its adaptive nature, the loads acting on the building envelop and the way they are transferred to the building skeleton can vary depending on the circumstances. This leads to complications regarding testing of the performance, since standardized testing methods might not be applicable directly and a holistic approach might be needed. The experimental testing should provide relevant information about the performance of individual components, but also about the system as a whole. Therefore, various experimental setups might be required, such as testing at component, sub-system and system level to obtain useful information concerning all relevant aspects of the expected structural response of the facade during its service life.

The structural behaviour of adaptive facade components is greatly affected by the way they are attached to the main building frame. Sometimes, the joints need to accommodate significant strains or are subjected to cyclic loading and can consequently accumulate damage. Consideration for local failure phenomena in these sensitive parts is hence important, when assessing the performance of the facade as a whole. Furthermore, movable elements need to be secured to the system and prevented from falling out, even in case of unforeseen circumstances. Thus, considerations of structural integrity and robustness are highly important for adaptive facades and scenarios of exceptional situations such as i.e. extreme winds, explosions and impacts might be important.

Adaptive facades are complex systems with a complicated set of requirements. To deal with verification of such requirements through testing the top-level design specifications can be propagated down to various subsystem and component levels in a consistent and efficient way as shown in case of a facade development

ACCEPTED MANUSCRIPT

project by Flansbjer et al. [22]. This process is often supported by numerical modelling, using i.e. the Finite Element method, to simulate different testing configurations and study the effect of changing various design parameters.

During the facade system development, desirable targets of structural performance are identified together with other aspects such as architectural, functional, structural, economic, environmental etc. These structural performance goals are then broken down into verifiable structural requirements concerning component behaviour, material and connection characteristics. With this the tasks for testing those characteristics are defined and the structural performance is validated following a bottom-up approach (Figure 3).

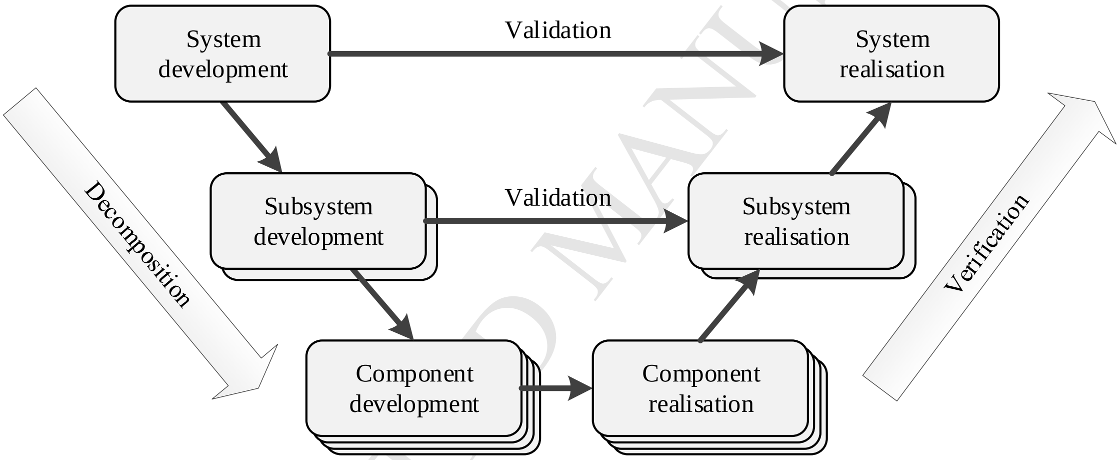


Figure 3. Facade system structural performance validation through testing (figure adapted from [22]).

The validation through testing is typically and naturally builds upon standardised testing procedures since construction product manufacturers, testing institutes and authorities are familiar with those methods. Reasonable modification of standard tests is, however, often needed to study specific questions related to the performance of adaptive facades.

ACCEPTED MANUSCRIPT

3.2 Structural adaptivity for testing

Structural adaptivity is beyond traditional structural engineering, which typically deals with systems in static and dynamic equilibrium. In a structurally adaptivity system the equilibrium might change gradually involving large deformations and movements. The system is thus often a mechanism where the stiffness, the geometry or the external forces are controlled either ‘manually’ or ‘automatically’. ‘Manually’ and ‘automatically’ here refers to the extent the structural response to the changes in the environment is regulated.

From a pure structural point of view, adaptive facade systems can take several forms, involving different combinations of materials and kinetic mechanisms. More in detail, extreme conditions could derive from exceptional design loads (i.e., impact, fire, natural hazards, etc.), but also from an unsafe geometrical / mechanical variation of restraints (activation systems).

In this sense, the actual lack of specific regulations for ‘general’ adaptivity forms, makes it also difficult to make a clear distinction between structural testing methods, procedures and tasks for the same systems.

Generally speaking, for a given adaptive facade, testing should first focus on selected regions/components which are representative of the most common (and/or most critical) elements of the full building envelope. As such, this selection is strictly related to the complexity of a given detail / assembly, or to the condition under and frequency at this component /assembly is expected to move / deform [23].

Further difficulties related to the structural performance assessment by testing (compared to conventional facades) can arise when specific Ultimate Limit State (ULS) and Service Limit State (SLS) performances should be ensured for a given adaptive system. In the majority of the cases, adaptive skins result from free-form design, complex technical solutions and multiple kinematics. Field testing, finally, should always include accurate investigations at the facade-to-substructure interface. In Table 2, some suggestions are provided. However, given the relatively high number of possibilities for adaptiveness (including adaptive features and control strategies), it would be impossible to make a comprehensive list.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Table 2. Examples of performance parameters for the structural characterisation of adaptive facades by testing (recommendations from the EU-COST TU1403 'Structural' Task). Specific configuration definitions are reported in [1].

Performance parameter	**Configuration to assess**	**Testing recommended at:** **F= full-scale / assembly level** **S = small-scale / single component level**
Structural behaviour	Active cable length control and active cable prestress control through mechanical actuators, for cable-stayed facades to optimise material use (depending on the loading conditions)	F+S
	Shape memory alloys (with increased temperature the mechanical properties of a cable change => higher stiffness, higher prestress)	F+S
	High-strength thin glass (flexibility combined with high-strength)	F+S
	Fatigue of moving components / materials (depending on the expected design loads)	S
Safety (ULS)	Reinforcement that acts in the event of damage/overload	F
Flexibility (SLS)	Maximum deformations deriving from service design loads should not exceed a certain reference limit	F
Safety under extreme actions / hazards (fire, explosions, seismic events, hurricanes, flooding, etc.)	In case of hurricane (solid) solar shutters could close to protect the facade and (more importantly) the building occupants. These shutters are hence intended as sacrificial components.	F+S
	Fire shutters integrated in the facade in the event of fire	F
	Foam interlayers/paints that respond/act in the event of fire.	F
	Inflatable barriers or shutters, in case of flooding (to a certain water level, i.e. 50cm)	F
	Airbags for facades	F
	Fuses / shock absorbers / dampers, in case of explosion or seismic action	F+S
	Use of the whole facade as a sacrificial layer / shock absorber / energy dissipator	F+S
Durability	Self-healing materials, such as self-healing concrete	F+S
	Quick / cheap retrofitting of facades or facade elements through 3D printing technologies (regularly update your facade by cheap 3D printed polymer components that may deteriorate structurally much quicker than conventional materials such as aluminium, but at the same time being able to respond to the latest requirements/regulations)	F+S
	Fatigue of moving components/materials (depending on the expected design loads)	F+S

The key aspect in Table 2 is that – for structural purposes – the safe performance of a given adaptive skin may require a different number and / or type of experiments, both at the component and at the assembly level. At the same time, from Table 2, it is possible to notice that the required experimental method can be different for a given dynamic skin (when the building class of use, or design load modifies), also in presence of similar mechanical features. In other words, the basic structural requirements that an adaptive façade needs to fulfil to provide appropriate reliability levels from both a human safety and economic perspective can involve different experimental methods (even non-conventional), depending on the source and typology of adaptivity.

As also discussed in [1], adaptive facades are not standard assemblies and their performance is hardly tangible by out of-the-box testing procedures. On the other hand, there are established tests to claim compliance with essential structural requirements, therefore a holistic approach has to be applied. This could be done by an agreement among the customer, manufacturers of components and testing laboratory regarding declaration of the adaptive facade performance and selection of standards to be applied or adjusted. In some cases, the development of additional and unique tests is a major part in adaptive facade design.

For example, thinking about out-of-plane movement of adaptive facades, there could be joints that allow water to penetrate without impact to water-tightness; however, water could remain and enclosed when the facade moves back its original shape. The movable parts of adaptive facades can also affect their lifetime with regard to the possible cyclic load and fatigue of individual parts. Experimental verification of the durability and reliability will always require individually designed test procedures. Also, under wind loads, moving parts can cause changes in airflow, especially in the case of high-rise buildings which may require subsequent verification of the building model behaviour in the wind tunnel. Marutaa et al. [24], in this regard, reported experimental data for a model in 1/300 scale of a high-rise house (square section, 75m the height). There, it was shown that wind pressure effects are strongly affected by the surface roughness, particularly near the leading edge of the side walls, where local severe peak pressures are expected to decrease with increasing roughness. The latter, in fact, can reduce the development of conical vortices occurring at the extreme regions (i.e., lower and higher parts) of buildings.

ACCEPTED MANUSCRIPT

Regarding existing standards and test procedures, the experimental testing of adaptive facades could be consequently a challenging task. There are probably various options to customize test facilities to the adaptive behaviour. Therefore, a careful preparation and a lot of ‘what if’-thinking is the key factor for satisfactory adaptive facade tests.

4. Selected experimental testing methods of facade components and systems

Beside the recommended testing procedures – actually in use for the certification and classification of conventional facades (see also Section 2) – the innovativeness of adaptive skins often requires the use of dedicated testing methods. These could result from the use of special / unconventional construction materials, as well as from the presence of time-varying boundaries (i.e., due to kinematic mechanisms, or degradation of material properties, etc.), as well as extreme design loads, where the adaptiveness of novel skins may lead to critical performances, compared to static facades. While the certification testing procedures are limited to selected performance parameters assessment, in this regard, experimental testing may involve novel loading configurations, measurement techniques, etc. The following sections, in this regard, are aimed at providing a general view on the potential and reliability of experimental methods for adaptive facades, with specific attention for structural performance aspects.

4.1 Testing of mechanical connections

Regardless of whether it is a conventional or an adaptive facade, today's design is characterized by a variety of building materials. Besides ordinary steel or wooden components and glass panes, a wide range of structural facade components exists. These can be made of plastics, textiles, transparent foils or single layer polymer membrane, or a multitude of sandwich structures that are characterized by the interaction of different materials. In all these possible configurations, a key role is assigned to mechanical connections and joints, allowing the physical interaction and even complex dynamic performance of multiple facade components. Contemporary architecture, in fact, does not limit the use of materials or surface finishes, resulting in relatively large variability of materials and their joints. In most cases, however - especially when

ACCEPTED MANUSCRIPT

using glass or non-conventional materials - there are no guidelines or standard procedures for the appropriate experimental verification of joints.

Requirements for the aesthetic appearance of buildings limit the use of individual types of mechanical fasteners which are indispensable either for connections of single components to a supporting structure, or to one component to another. For example, there is a trend in the last 30 years to maximize transparency in case of glass facades and reduce the size of glass supports and visibility of connections. Screws with a countersunk head or welds are often used, thus the surface of the facade cladding remain smooth without any disruption by the raised heads of bolted supports. New promising developments in adhesively bonded connections for civil engineering applications provides new possibilities for facade connections and in the same time associated problems such as durability and long-term mechanical properties.

Procedures for the design and experimental verification of common mechanical fasteners used for the connection of steel, thin-walled cold-formed profiles or wooden framing members are given in the relevant European standards, see for example the EN 1990, or EN 1993-1 -1 [25] and EN 1995-1-1 [26]. The ETAG 034 also states requirements on an external cladding, mechanically fastened to a frame and specifies corresponding test methods and procedures in the fields of mechanical resistance and stability, safety in case of fire, hygiene, health and environment, safety in use, protection against noise, energy economy and heat retention, aspects of durability and serviceability [11]. In the case of the design of structural glass pane connections [27], normative documents or rules for their experimental verification are not yet available.

Bolted connections for glass applications have been used in a wide variety for decades due to requirements on minimal visual impact. Their design is based on the experience from practice and the results of experimental testing. Bolted connections generate high local stresses because of the bolt is subjected to shear forces, whereas the connected members are locally subjected to compressive stress at the location of contact with the bolt and tensile stresses on side of the bolt hole. In the case of brittle materials such as glass, the material is unable to accommodate local stress concentrations by yielding such as elasto-plastic materials, and it represents the major problem of bolted connections for brittle materials. Through the years of application of bolted connections for facades, the protruded bolt connection was evolved further in

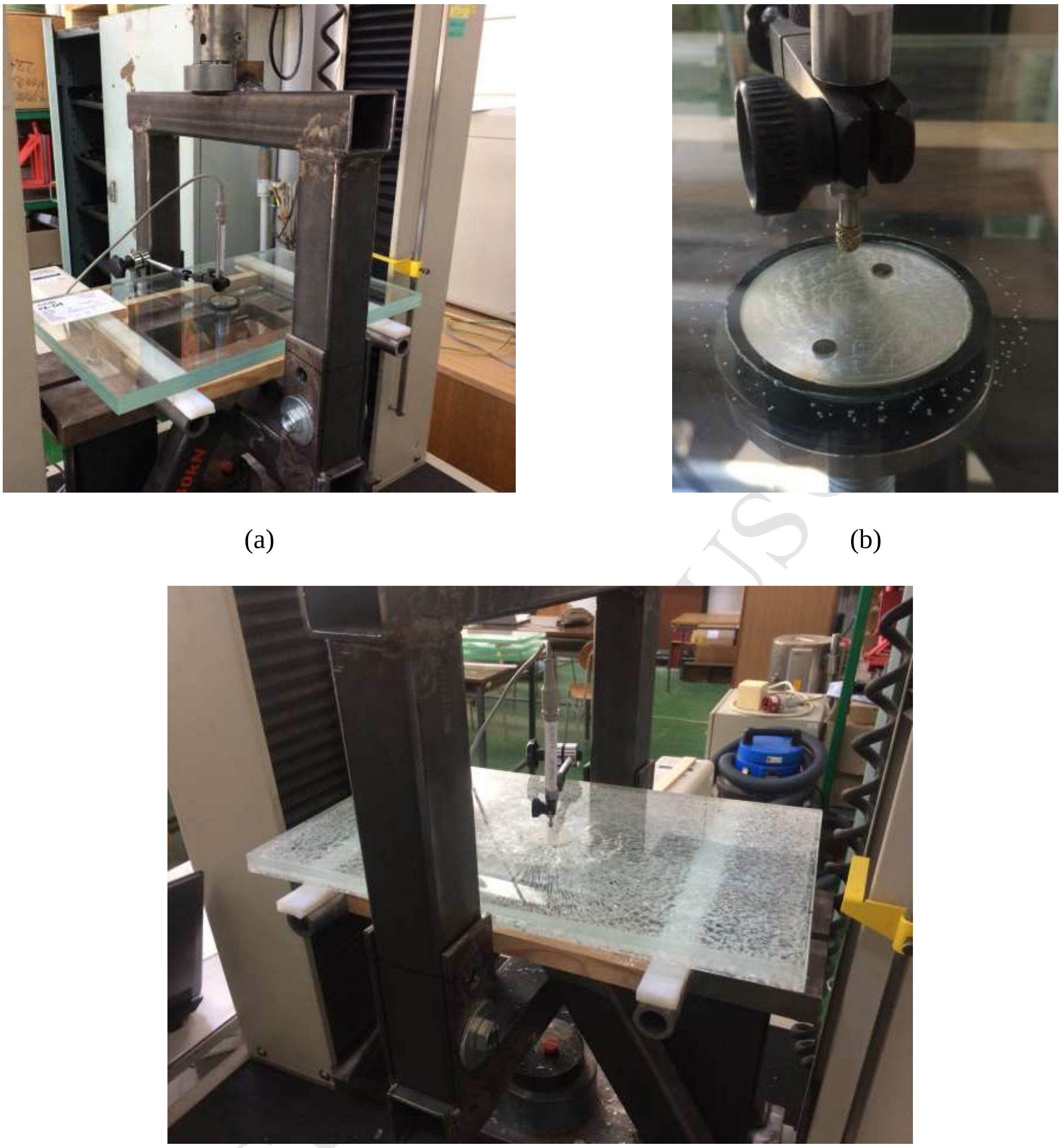
ACCEPTED MANUSCRIPT

countersunk fixing that uses conical holes and bolts to resist out-of-plane loading and obtain smooth external surface without any protrusions. Relatively recently developed articulated bolts, which includes a ball and socket, allows free rotation of the facade panel and reduce stress concentrations [28].

Countersunk bolts can be embedded during the lamination process of laminated glass panels where interlayer creates an adhesive bond between glass plates and a metal component of the bolt. Embedded countersunk bolts for laminated glass panes can be used as an alternative to the conventional bolted connections, however, their use is limited due to the lack of knowledge about the behaviour under the short / long-term loading and fatigue. Embedded countersunk bolts for laminated glass were recently experimentally tested at the Czech Technical University (CTU) in Prague, see Figure 4(a). The typical failure pattern is shown in Figures 4(b) and (c), where the embedded metal part was first delaminated from the glass pane, together with the propagation of several small bubbles around it, while subsequently the failure of glass followed.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT



(a)

(b)

(c)

Figure 4. Pull-out test for an embedded countersunk bolt. (a) Test set-up; (b) delamination of the bolt head and bubbles around the bolt head; (c) failure of the glass pane with the hole for the countersunk bolt.

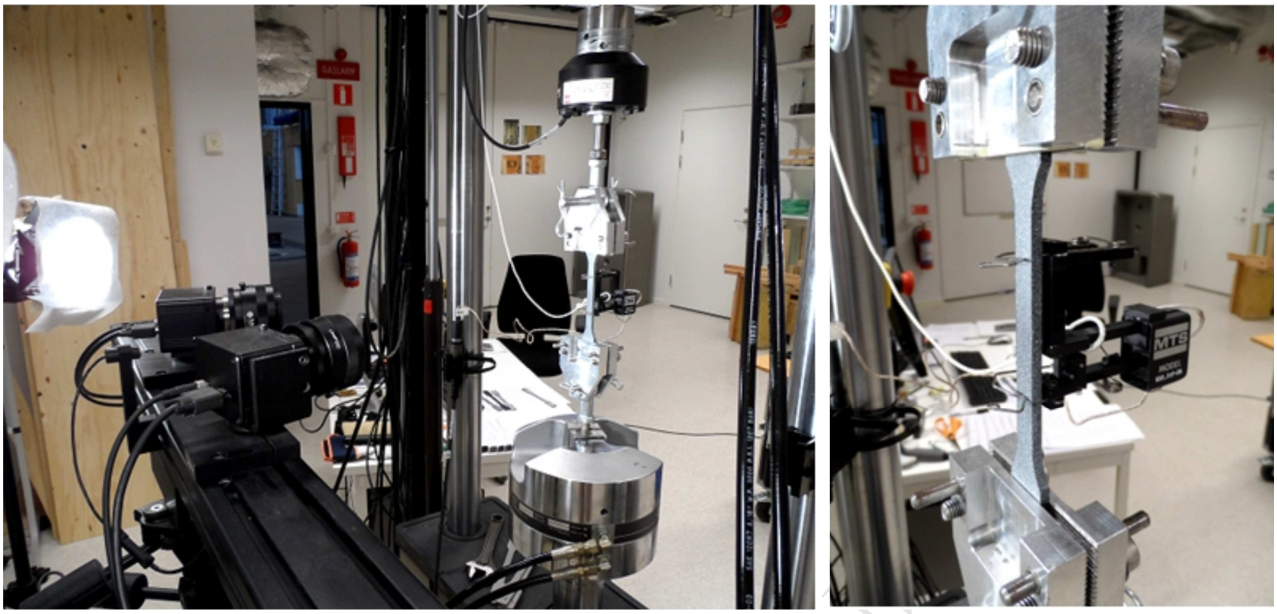
ACCEPTED MANUSCRIPT

4.2 Testing of adhesive joints

Requirements for the aesthetic appearance of buildings, together with a more uniform stress distribution, generally lead to different types of connection, for both conventional claddings or adaptive facades. Adhesive connections, in this regard, provide a number of advantages such as a more uniform stress distribution along the connection (as a function of the adhesive stiffness and joint geometry), joining dissimilar materials, including further positive aspects like low weight of the load-bearing components, smooth surface of the cladding elements and a marked reduction of local thermal bridges.

For these reasons, structural silicones sealants have been used in facade joints for many years, given their high durability. Silicone adhesives are known as flexible adhesives with relatively low strength (approximately 1 MPa) and Young´s modulus, which are applied in several millimetres thickness. For that reason, structural silicones are often used for 4-side bonding systems, thus a low strength is compensated by a quite large bonded area. The procedures for experimental verification mechanical properties of silicone joints are given by ETAG 002 [29].

ACCEPTED MANUSCRIPT



(a) (b)

Figure 5. Tensile test of epoxy adhesive with combined measurement of strain using extensometer and Digital Image Correlation (DIC) techniques [30].

Apart from conventional testing approaches, contact-less techniques can be also implemented to assess the mechanical properties of a given adhesive joint. The Digital Image Correlation (DIC) approach, in this regard, can offer reliable predictions and robust background, in addition to common measurement techniques, see for example Figure 5 and [30].

The so-called, recently developed Transparent Structural Silicone Adhesive (TSSA) combines excellent transparency and superior mechanical characteristics (see for example [31]). It is usually used for metal-to glass connection without penetration of the glass members. In comparison to 'standard' silicone sealants, in addition, it shows higher stiffness and strength, which makes it suitable for structural applications [32].

The requirements for larger, disrupted facade elements from various materials, as well as slender support frames and structures, lead to the requirements on higher strength of joints to be able to transfer higher loading. Subsequently, semi-rigid adhesives (mostly polyurethanes and acrylates) with higher strength than flexible silicones and reasonable elongation at break are needed for current facade adhesive joints. Also,

ACCEPTED MANUSCRIPT

recently developed structural silicones provide greater tensile strength up to 3 MPa according to manufacturer's documents [33, 34] and even a new generation of structural silicones are designed for point fixings with 1 mm thick bond-line and tensile strength 4.5 MPa [34].

An adaptive facade is an engineering application with specific requirements, such as durability and compatibility despite joining unconventional materials. The design life time and the environmental ageing effects of adhesive connections are hence fundamental aspects for the knowledge completion about polymeric adhesives in facades. Actually, several codes and guideline documents are available for the assessment of adhesive joints durability (see for example [35, 36], etc.). However, these regulations are specific for the automotive or the aerospace industries, hence cannot be directly extended to facade connections, due to a wide series of intrinsic features and differences, like for example the joining materials, the operational environments of joints, the in-service conditions, included loading configurations, as well as curing properties, joint geometry, manufacturing conditions and joint life time. In the latter case, it is important to remind that the actual / conventional service life of adhesively bonded connections for civil engineering and building applications is significantly larger than the service life of adhesives assemblies for aerospace structures. In this context, the durability of adhesive connections for facade applications has been largely investigated at the Klokner Institute of CTU Prague. The experimental programme (still in progress) included two adhesive samples with different chemical base (a two-part acrylate and a Silane Terminated Polymer (STP)), together with four batches (i.e., a reference set, extended cataplasm, neutral salt spray test, or immersion in water). Various types of substrate and treatment were also considered for the joints (i.e., blank aluminium with a smooth or roughened surface, anodized aluminium, Zn-electroplated steel with the smooth or roughened surface), see [37] for a detailed description of test methods. Worth of interest is that the available experimental results showed that the most critical ageing method cannot be identified easily, for facade adhesive joints, because the mechanical degradation effects are different, as far as the chemical base of adhesives modifies. Consequently, further extended studies and dedicated tests are hence required.

ACCEPTED MANUSCRIPT

4.3 Impact testing

In additions to typical loads acting on the adaptive building enclosures, impact loads may in some cases be decisive factors for its design, both, in terms of safety in use and maintaining adaptive performance characteristics. Elements of adaptive facades may be subjected to different types of impact, depending on its nature (i.e., hard body or soft body) and direction (i.e., acting from inside or outside of the building). In addition, the impact performance of an adaptive facade panels may be influenced by many factors including the flexibility of the element itself and the stiffness of the supporting structures, see for example [38-42]. Therefore, as a general rule, different impact locations should be considered for a given facade panel, namely represented by its central region, the midpoint section, the panel edges, the regions in the vicinity of supports and any other key impact locations that may affect the structural safety and kinematic performance of the facade as a whole.

Several standards and technical recommendations specify the principles of testing of building facade elements subjected to impact actions [43-46]. In general, all the standard procedures involve a mass making into pendulum motion impacting selected areas of the element with a defined impact energy depending on the mass of the body and drop height (see also Figure 6).

The “hard body” impact test simulates the impact resulting from a hard object accidentally falling against the panel. Such a configuration includes two hard body masses for testing, equal to 0.5 and 1 kg, released from an reference height that produces an impact energy from 3 to 10J, respectively. The “soft body” impact test simulates an impact resulting from a person falling against the panel. To this aim, the soft body impactor has a typical mass of 50kg and is built with a leader bag filled by glass spheres [43-45], or can consists in two pneumatic tires with a steel mass [46]. Accordingly, the expected impact energy is in the range of 120 to 500J.

In such a kind of testing protocol, finally, special consideration should be spent for the fundamental dynamic parameters of the sample to assess, namely the vibration frequencies and damping capacity, and their sensitivity to the actual boundary conditions (see [48]).

ACCEPTED MANUSCRIPT

Figure 6. Soft body impact test of point-fixed laminated glass panel [47].

4.4 Fire resistance testing

Within the design configurations that a facade may be required to sustain, fire loading certainly represents a critical condition requiring appropriate safety levels and experimental methods.

Figure 7, for example, shows a fire experiment according to SP Fire 105, a dedicated test method for full-scale facades, as in use at the fire lab facilities of RISE Research Institutes of Sweden (RISE) in Sweden (see [49] for further details). Fire resistance assessment investigations, as known, represent a key topic for buildings in general, but especially for facades performance evaluations, both in the case of glazing components - typically highly sensitive to elevated temperatures – but in general for building systems in which combustible materials are used (see for example [50-54], etc.). The SP Fire 105 test method, in particular, specifies a procedure to determine the reaction to fire of materials and construction of external wall assemblies or facade claddings, when exposed to fire from a simulated apartment fire with flames emerging out through a window opening. The behaviour of the construction, the materials and the fire spread

ACCEPTED MANUSCRIPT

(flame spread) in the wall/cladding can be studied (Figure 7). To reliably assess the fire performance of the entire system, the facade needs to be tested in full-scale. Due to the differences in building regulations throughout the countries, large differences can be observed in the testing methods in Europe. Accordingly, a harmonised European methodology for testing and classification of facade systems is currently under development, allowing to assess all relevant modes of vertical fire spread.

(a) (b)

Figure 7. Fire lab facilities at RISE Research Institutes of Sweden. Example of (a) full-scale experimental setup and (b) damage propagation for a facade exposed to fire loading.

4.5 Blast resistant testing

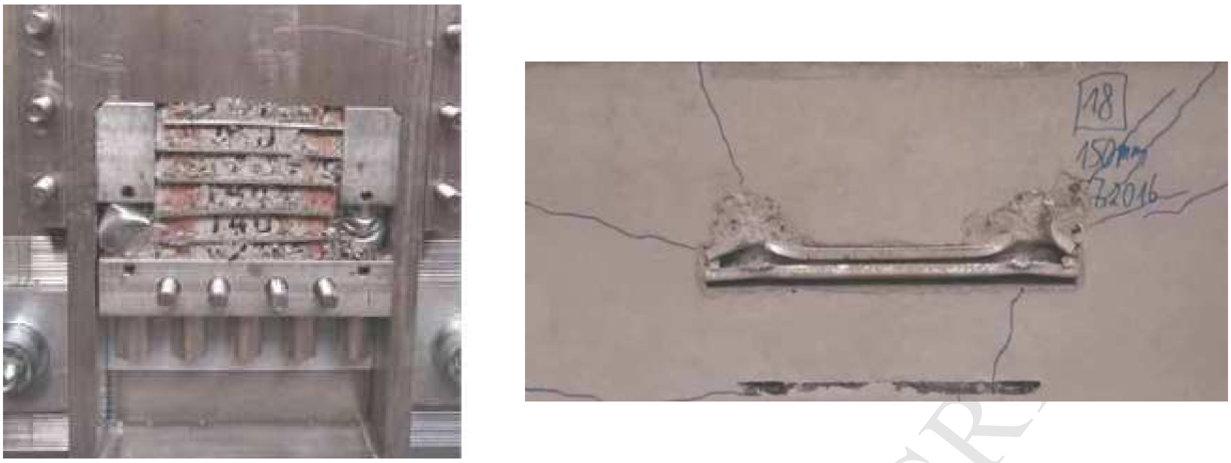
The determination of the blast protection level of civil engineering buildings components against explosive effects, in general, represents a topic of crucial importance, in current design practice. Even much more catastrophic effects can be expected – given a blast event – in the case of envelopes and facades, where these systems are required to provide the first line of defence of the building occupants. However, some crucial aspects still need to be properly addressed.

ACCEPTED MANUSCRIPT

First, some key aspects for the optimal design of blast resistant structures have been only marginally considered in the last decades, and currently require urgent and appropriate regulations. This is especially true in terms of experimental testing, with careful consideration for facades, where the intrinsic material brittleness is the major influencing parameter for blast-resistant assemblies. While the blast assessment of buildings and complex systems is in fact usually achieved by means of experimental investigations, general regulations and guidelines are currently missing for curtain walls, with the exception of limited documents / test configurations that do not reflect the variability of geometrical / mechanical features of innovative dynamic skins. In this regard, the European Reference Network for Critical Infrastructure Protection (ERNCIP) - Thematic Group “Resistance of Structures to Explosion Effects” is currently attempting at developing a set of specific guidelines and recommendations to harmonise test procedures in experimental testing of facades (especially glazed systems) under blast (see for example [55, 56]).

Experimental testing may then be reliable and useful to address and optimize novel facade components. In [57], for example, special brackets have been tested and proposed as an efficient solution for the mitigation of conventional glass curtain walls under blast, see Figure 8. The dissipative joint aims at reducing the stiffness of conventional rigid restraints at the interface between curtain walls and the building sub-structures (i.e., the inter-storey floor slabs), based on a mechanism able to activate under high strain impulsive events only, while preserving the structural load bearing capacity under ordinary loads. As far as part of the incoming blast energy can be dissipated via sacrificial components, this can strongly reduce the expected effects on the facade components, hence resulting in enhanced dynamic performance and optimized design assumptions.

ACCEPTED MANUSCRIPT



(a) (b)

Figure 8. Experimental testing of dissipative brackets for facades under blast [57]: (a) bracket detail (front view) and (b) damaged slab connection after testing.

4.6 Multi-functional outdoor testing

In conclusion, it is generally recommended to perform the experiments in laboratories and facilities that have accreditations to relevant test methods for facades, when the final intention is to certify products. According to EC regulation No 765/2008, the ‘accreditation’ by a National Accreditation Body confirms that a Conformity Assessment Body meets the requirements set by harmonized standards and, where applicable, any additional requirement (including those set out in relevant sectorial schemes) to carry out a specific conformity assessment activity. A full list of European accredited laboratories, including their key testing methods and certification bodies, can be usually found in the databases of the National Accreditation Bodies, which are associated with the European cooperation for Accreditation (EA), see [58]. Figure 8, in this regard, presents a selection of EU facilities that are accredited for a large number of experimental methods for the structural performance assessment of facades and curtain walls (with special consideration for EU-COST Action TU1403 Partner Countries).

ACCEPTED MANUSCRIPT

Given such a general rule, however, the recommendation to test in accredited laboratory cannot be fully applicable in all cases, because the actual offer is limited, especially in case of adaptive facades. Careful consideration is required, for example, when extreme design loads are expected.

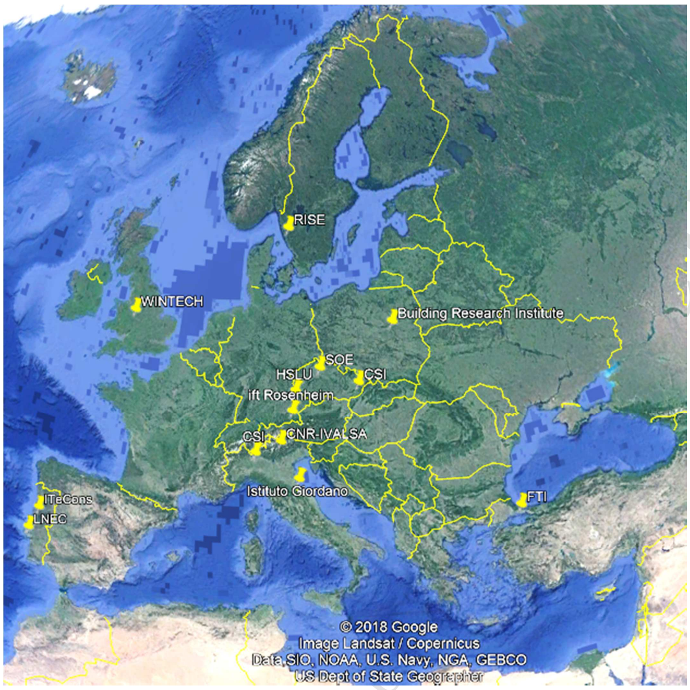


Figure 9. Selection of accredited European testing laboratories for facades assessment (EU-COST TU1403 Partner Countries).

Among the selection of Figure 8, in this regard, the Facade Engineering Centre (CC FM) at the Lucerne University of Applied Sciences (HSLU, Switzerland) provides one of the biggest facade and window test facilities in Europe. The facility is especially designed to be used beyond standard test methods. For example, multiple storey facades can be tested with simulated floor slabs. Facades with high deflections, like cable facades, can also be tested.

The test rig is designed as a continuously adjustable, outdoor facility (see Figure 10) with an accessible pressure chamber (2.5m deep) and external sprinkling. In case of high deflecting facades, a maximum deformation up to 0.9m can be allowed into the chamber.

The test facility has the following specifications:

ACCEPTED MANUSCRIPT

Dimensions	8×12 m^2
Pressure	± 10000 Pa (depending on tightness, fan max 800 m^3/h)
Pressure pulse	-3000 Pa to 3000 Pa within 5 seconds
Driving rain	up to 4 L/(m^2 min)

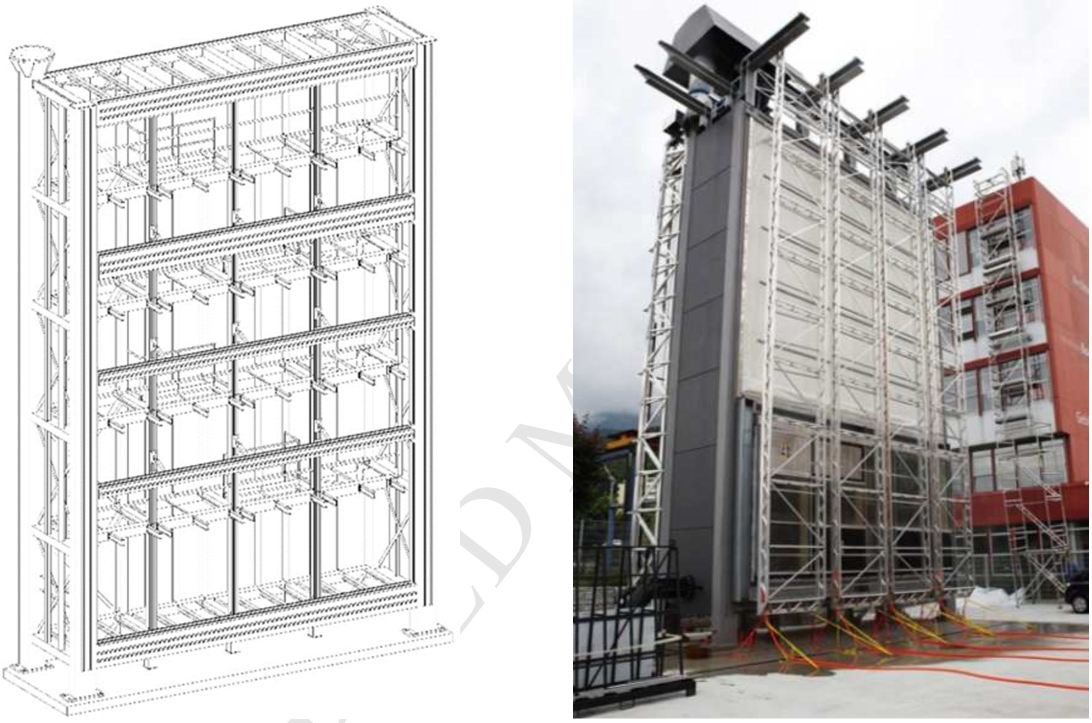

(a) (b)

Figure 10. CC FM test facility at HSLU (Switzerland): (a) 3D sketch and of (b) photo reproduced from [59] (Copyright ® HSLU, 2014)

Wireless instruments ensure a straight forward handling during installations, as well as during testing. The technical centre is located beside the facade test facility and is divided in two parts; the engine part and control part. The engine part contains the devices for pressure generation and rainwater with a water reservoir for independent water supply of the main water supply. In the control part, the monitoring and

ACCEPTED MANUSCRIPT

control computer based on HOLTEN test equipment is located. All signals of pressure and wireless displacement transducers are collected from the control part.

Test procedures can either manual or programmed controlled. For standard procedures appropriate program routines are available. For specified observations or a detailed view in individual procedure steps the facility can be manually controlled. In case of standardized testing, results and classification output can directly be given, such as (a) test metrics; (b) air tightness; (c) water penetration; (d) static load resistance; (e) dynamic load resistance; (f) deflections.

While the test rig is primarily designed to be used beyond standard test procedures, the CC FM has strong experience with unconventional test procedures that could be relevant for adaptive facades. For example, this is the case of hurricane impact testing, involving exceptional dynamic performances for the façade components. Accordingly, further adaptivity / flexibility for adaptive facades is also required for the testing infrastructures.

5. Conclusion

In this paper, an insight on novel adaptive facades was reported, with special care for the structural performance assessment of smart envelopes. Although adaptive facades are getting gradually more common in modern building skins, their structural design still represents a challenging task. Major issues are related to the characterisation of their mechanical performance, even in lack of specific design regulations and provisions in support of engineers for appropriate experimental testing approaches. In this regard, the recent outcomes of the ‘Structural’ Task Group involved in the EU COST Action TU1403 were briefly summarised in this review paper, aiming at discussing the existing standards and testing methods for conventional facades, and pointing out the key features of adaptive skins and the need of dedicated procedures for their performance characterisation based on experiments.

Firstly, for performance assessments according to EN 13830 or ETAG 034 standardized test procedures for static facades represent a challenge for adaptive facades. There, a given adaptive façade can have different

ACCEPTED MANUSCRIPT

performances (depending i.e. on system change, activation mechanism, triggering event), and thus resulting in different performance indicators to properly evaluate. The applicability of conventional experimental test methods to adaptive facades, given the favourable or unfavourable adaptive states and the possible interactions between test procedures and adaptivity, must be considered carefully. Additional experimental tests might be also necessary, to offer appropriate safety levels to adaptive skins, even under extreme design loads or unfavourable mechanical conditions. A generalized methodology and testing suggestion – i.e., able to cover all the possible structural adaptivity forms - is however currently not possible. In some cases, unconventional experimental approaches (inclusive of innovative monitoring systems) may be also required. The final result is an adaptivity of experimental strategies that should be able to point out the possible critical aspects and performances of structurally efficient adaptive facades.

Acknowledgement

This paper collects some outcomes of the 'Structural' Task Group within the EU-COST Action TU1403 'Adaptive Facades Network' (2014-2018, http://www.tu1403.eu).

In this regard, the COST Association is gratefully acknowledged for providing excellent research networking between the involved authors, as well as with international experts.

All the Network members that supported the 'Structural' TG activities are also acknowledged for their valuable cooperation.

References

[1] C Bedon, D Honfi, K Machalická, M Eliášová, M Vokáč, M Kozłowski, T Wüest, F Santos, N Williams Portal (2019). Structural characterisation of adaptive facades in Europe – Part I: an insight on classification rules, performance metrics and design methods. Journal of Building Engineering, *accepted, in print*

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

[2] C Bedon, X Zhang, F Santos, D Honfi, M Kozłowski, M Arrigoni, L Figuli, D Lange (2018). Performance of structural glass facades under extreme loads – Design methods, existing research, current issues and trends. Construction and Building Materials, 163: 921-937

[3] C Bedon, D Honfi, M Kozłowski, K Vokáč Machalická, F Santos, T Wüest, M Eliášová, M Vokáč (2018). Key structural aspects for adaptive facades - Activity progress from the EU-COST Action TU1403 'Structural' Task Group. International Journal of Structural Glass and Advanced Materials Research, volume 2(2018): 135-154, doi: 10.3844/sgamrsp.2018-135.154

[4] LG Bakker, ECM Hoes-van Oeffelen, RCGM Loonen, JLM Hensen (2014). User satisfaction and interaction with automated dynamic facades: A pilot study. Building and Environment, 78: 44-52

[5] S Attia, A Luna Navarro, M Juaristi, A Monge-barrio, S Gosztonyi, Z Al-Doughmi (2018). Post-occupancy evaluation for adaptive facades. Journal of Facade Design and Engineering, 6(3): 1-9

[6] C Bedon, C Amadio (2018). Enhancement of the seismic performance of multi-storey buildings by means of dissipative glazing curtain walls. Engineering Structures, 152: 320-334

[7] K Kazmierczak (2010). Review of curtain walls, focusing on design problems and solutions. Proceedings of the Building Enclosure Science & Technology Conference (BEST2) – Design and Rehabilitation

[8] Ng C – Aurecon Singapore (Pte) Ltd (2012). The essential of facade performance testing. Glass on Web, *https://www.glassonweb.com/article/essential-facade-performance-testing*

[9] EN 13830: 2003. Curtain walling - Product standard. CEN - European Committee for Standardization, Brussels, Belgium

[10] ETAG 034: 2012. Guideline for European Technical Approval of Kits for External Wall Claddings. EOTA - European Organisation for Technical Assessment, Brussels, Belgium

[11] European Parliament (2011). Regulation (EU) No. 305/2011 of the European parliament and of the council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC. Official J. European Union, 88: 5-43

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

[12] E Ilter, A Tavil, OC Celik (2015). Full-scale performance testing and evaluation of unitized curtain walls. Journal of Facade Design and Engineering, 3(1): 39-47

[13] TR Brewer, JE Crawford, KB Morrill, J Abraham (2016). Design, analysis, and testing of a blast-resistant building facade. In. J. Comp. And Exp. Meas., 4(3): 191-200

[14] EN 12153: 2000. Curtain walling – Air permeability – Test method. CEN - European Committee for Standardization, Brussels, Belgium

[15] EN 12179:2000. Curtain walling - Resistance to wind load - Test method. CEN - European Committee for Standardization, Brussels, Belgium

[16] EN 12155:2000. Curtain walling. Watertightness. Laboratory test under static pressure. CEN - European Committee for Standardization, Brussels, Belgium

[17] EN 1027:2016. Windows and doors - Water tightness - Test method. CEN - European Committee for Standardization, Brussels, Belgium

[18] F Favoino, RGCM Loonen, M Doya, F Goia, C Bedon, F Babich (2018). Building performance simulation and characterisation of adaptive facades – Adaptive Facade Network. TU Delft Open for the COST Action 1403 "Adaptive Facade Network", ISBN 978-94-6366-111-9, 189 pages. Available online: *http://tu1403.eu/wp-content/uploads/Vol-3-2_for-web-Open-Access_9789463661119.pdf*

[19] EN 1932:2013. External blinds and shutters - Resistance to wind loads - Method of testing and performance criteria. CEN - European Committee for Standardization, Brussels, Belgium

[20] EN 14351-1:2006+A2:2016. Windows and doors - Product standard, performance characteristics - Part 1: Windows and external pedestrian doorsets. CEN - European Committee for Standardization, Brussels, Belgium

[21] EN 1026:2016. Windows and doors - Air permeability - Test method. CEN - European Committee for Standardization, Brussels, Belgium

[22] M Flansbjer, D Honfi, D Vennetti, N Williams Portal (2016). Structural Concept of Novel RPC Sandwich Facade Elements with GFRP Connectors. Proceedings of IABSE Congress Stockholm, 2016:

ACCEPTED MANUSCRIPT

Challenges in Design and Construction of an Innovative and Sustainable Built Environment. IABSE c/o ETH Hönggerberg, pp. 2172-2186, URN: urn:nbn:se:ri:diva-27814

[23] MD Goncalves, R Jutras (2010). Evaluating the field performance of windows and curtain walls of large buildings. Proceedings of the BEST2 - Building Enclosure Science & Technology Conference. Available online: *https://www.brikbase.org/content/evaluating-field-performance-windows-and-curtain-walls-large-buildings*

[24] E Marutaa, M Kandaa, J Sato (1998). Effects on surface roughness for wind pressure on glass and cladding of buildings. J. Wind Eng. Industrial Aerodynam., 74-76: 651-663, doi: 10.1016/S0167-6105(98)00059-2

[25] EN 1993-1-3 (2006): Eurocode 3: Design of steel structures - Part 1-3: General rules - Supplementary rules for cold-formed members and sheeting. CEN - European Committee for Standardization, Brussels, Belgium

[26] EN 1995-1-1 (2004). Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings CEN - European Committee for Standardization, Brussels, Belgium

[27] C Bedon, M Santarsiero (2018). Transparency in Structural Glass Systems Via Mechanical, Adhesive, and Laminated Connections – Existing Research and Developments. Adv. Eng. Mater. 2018, 20, 1700815

[28] M Haldimann, M Overend, A Luible (2008). Structural use of glass. Zürich, Switzerland: International Association for Bridge and Structural Engineering, ISBN: 978-3857481192

[29] European Organisation for Technical Approvals. ETAG 002 Guideline for European Technical Approval for Structural Sealant Glazing Kit. Brussels, Belgium. 2012

[30] M Kozłowski (2014). Experimental and numerical analysis of hybrid timber-glass beams. PhD Thesis, Silesian University of Technology, Gliwice

ACCEPTED MANUSCRIPT

[31] A Hagl, A Wolf, S Sitte (2012). Investigation of Stress-whitening in Transparent Structural Silicone Adhesive. Paper presented at the Challenging Glass Conference 3: Conference on Architectural and Structural Applications of Glass, Delft

[32] M Santarsiero (2015). Laminated Connections for Structural Glass Applications. EPFL, Lausanne

[33] Dow Corning TSSA - Technical data sheet. Available online: *https://consumer.dow.com/en-us/document-viewer.html?ramdomVar=1690796101997710807&docPath=/content/dam/dcc/documents/en-us/productdatasheet/62/62-17/62-1709-dowsil-transparent-structural-si.pdf*

[34] Sikasil SG 550 - Technical data sheet. Available online: *http://ses.sika.com/dms/getdocument.get/a173fc1a-82d1-3602-8aa0-a138349f4534/pds_Sikasil_SG-550_e.pdf*

[35] RJ Hussey, J Wilson (1996). Structural adhesives: Directory and Databook. Chapman & Hall, ISBN-13: 978-0-412-71470-2

[36] EN 2243-2: 2005. Aerospace series – Non-metallic materials – Structural adhesives – Test method – Part 2: peel metal-metal. CEN - European Committee for Standardization, Brussels, Belgium

[37] K Machalicka, M Vokac, M Eliasova (2018). Ageing of adhesive connections for facade applications. Proceedings of Facade 2018 - Adaptive! – COST Action TU1403 “Adaptive Facades Network” Final Conference, pp. 175-180. Available online: *http://tu1403.eu/wp-content/uploads/COST_endconference2018_webversion.pdf*

[38] E Lamers, M Derkink (2008): Towards design rules for structures with glass panels during impact. Proceedings of Challenging Glass, pp. 369-376, IOS Press, ISBN 978-1-58603-866-3

[39] L Biolzi, A Bonati, S Cattaneo (2018). Laminated glass cantilevered plates under static and impact loading. Advances in Civil Engineering, Volume 2018, Article ID 7874618, doi: 10.1155/2018/7874618

[40] C Bedon, R Kalamar, M Eliasova (2017). Low velocity impact performance investigation on square hollow glass columns via full-scale experiments and Finite Element analyses. Composite Structures, 182: 311-325

ACCEPTED MANUSCRIPT

[41] A Ramos, F Pelayo, MJ Lamela, A Fernandez Canteli, ML Aenlle, K Persson (2015). Analysis of structural glass panels under impact loading using Operational Modal Analysis. Proceedings of IOMAC ’15 – 6th International Operational Modal Analysis Conference

[42] J Schneider, JD Wormer (2001). Impact loading on glass panes by soft body impact – Theoretical analysis and experimental verification. Proceedings of Glass Processing Days 2001

[43] EOTA (2003) - Technical Report TR001 - Determination of impact resistance of panels and panel assemblies

[44] CWCT Technical Note No 76 Impact performance of building envelopes: method for impact testing of cladding panels

[45] ISO 7892:1988 Vertical building elements -- Impact resistance tests -- Impact bodies and general test procedures

[46] EN 12600:2002 Glass in building. Pendulum test. Impact test method and classification for flat glass

[47] M Kozłowski, D Honfi (2019). Structural safety of glass components (Åforsk Foundation). Project Report (internal use only)

[48] C Bedon, M Fasan, C Amadio (2019). Vibration analysis and dynamic characterization of structural glass elements with different restraints based on Operational Modal Analysis. Buildings, 9(1): 13, doi: 10.3390/buildings9010013

[49] SP Technical Research Institute of Sweden (1994). SP Fire 105 - External wall assemblies and facade claddings - Reaction to fire. Issue no. 5, 16 pages, rev: 1994-09-09. Available online: *https://www.sp.se/sv/units/risesafe/safety/fire/Documents/Konstruktion*

[50] KTQ Nguyen, P Weerasinghe, P Mendis, T Ngo, J Barnett (2016). Performance of modern building facades in fire: a comprehensive review. Electronic Journal of Structural Engineering, 16(1): 69-86

[51] WK Chow, Y Gao, CL Chow (2006). A review on fire safety in buildings with glass facade. Journal of applied fire science, 16(3): 201-223

ACCEPTED MANUSCRIPT

[52] C Bedon (2017). Structural glass systems under fire: overview of design issues, experimental research, and developments. Advances in Civil Engineering, Volume 2017, Article ID 2120570, 18 pages, doi: 10.1155/2017/2120570

[53] M Kozlowski, C Bedon, D Honfi (2018). Numerical analysis and 1D/2D sensitivity study for monolithic and laminated structural glass elements under thermal exposure. Materials, 11(8): 1447, doi: 10.3390/ma11081447

[54] L Peng, Z Ni, X Huang (2013). Experimental and numerical study of fire spread upon double-skin glass facades. MATEC Web of Conferences, 9, 03009, doi: 10.1051/matecconf/20130903009

[55] C Bedon, A van Doormal, C Haberacker, G Husken, M Larcher, A Saarenheimo, G Solomos, A Stolz, L Thamie, G Valsamos (2014). A comparison of existing standards for testing blast resistant glazing and windows. Report EUR 27133 EN, ISBN 978-92-79-46168-2, doi: 10.2788/361383. Available online: *https://erncip-project.jrc.ec.europa.eu/sites/default/files/ReqNo_JRC94930_A%20comparison%20of%20existing%20standards%20for%20testing%20blast%20resistant%20glazing%20and%20windows.pdf*

[56] M Larcher, M Arrigoni, C Bedon, A Van Doormal, C Haberacker, G Husken. O Millon, A Saarenheimo, G Solomos, L Thamie, G Valsamos, A Williams, A Stolz (2017). Recommendations for a new generation of standards for testing numerical assessment of blast-loaded glass windows. Key Engineering Materials, 755: 121-130

[57] M Forch, F Wellershoff, G Lori, M Zobec, D Casucci, P Grosser (2018). Experimental testing of dissipative facade brackets. Proceedings of Facade 2018 - Adaptive! – COST Action TU1403 “Adaptive Facades Network” Final Conference, pp. 357-367. Available online: *http://tu1403.eu/wp-content/uploads/COST_endconference2018_webversion.pdf*

[58] EA - European Accreditation, *http://www.european-accreditation.org/*

[59] HSLU Luzern - Produktprüfungen bei Fenstern und Fassaden Der Fassadenprüfstand ist einzigartig in der Schweiz, *https://www.hslu.ch/en/lucerne-school-of-engineering-architecture/research/competence-centers/gebaeudehuelle/fassaden-und-metallbau/infrastruktur/produktepruefungen/*

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

1. Adaptive facades are increasingly used in buildings, but these novel skins lack in an appropriate structural characterisation
2. The paper gives a set of definitions and rules for structural performance assessment of adaptive skins
3. A classification approach is proposed for structural adaptive systems
4. Reliable metrics and structural performance indicators are suggested
5. A discussion of experimental methods and regulations for structural testing is presented

ACCEPTED MANUSCRIPT