Structural characterisation of adaptive facades in Europe – Part I: Insight on classification rules, performance metrics and design methods

Chiara Bedon[a,*], Dániel Honfi[b], Klára V. Machalická[c], Martina Eliášová[d], Miroslav Vokáč[c], Marcin Kozłowski[e], Thomas Wüest[f], Filipe Santos[g], Natalie Williams Portal[b]

[a] *Department of Engineering and Architecture, University of Trieste, Trieste, Italy*
[b] *RISE - Research Institutes of Sweden, Gothenburg, Sweden*
[c] *Klokner Institute, Czech Technical University in Prague, Prague, Czech Republic*
[d] *Faculty of Civil Engineering, Czech Technical University in Prague, Prague, Czech Republic*
[e] *Faculty of Civil Engineering, Silesian University of Technology, Gliwice, Poland*
[f] *Institute of Civil Engineering, Lucerne University of Applied Sciences and Arts, Lucerne, Switzerland*
[g] *CERIS, ICIST and Departamento de Engenharia Civil da Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa, Quinta da Torre, Caparica, Portugal*

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ABSTRACT

Adaptive facades are increasingly used in modern buildings, where they can take the form of complex systems and manifest their adaptivity in several ways. Adaptive envelopes must meet the requirements defined by structural considerations, which include structural safety, serviceability, durability, robustness and fire safety. For these novel skins, based on innovative design solutions, experimentation at the component and / or assembly level is required to prove that these requirements are fulfilled. The definition of appropriate metrics is hence also recommended. A more complex combination of material-related, kinematic, geometrical and mechanical aspects should in fact be properly taken into account, compared to traditional, static facades. Accordingly, specific experimental methods and regulations are required for these novel skins. As an outcome of the European COST Action TU1403 'Adaptive facades network' - 'Structural' Task Group, this paper collects some recent examples and design concepts of adaptive systems, specifically including a new classification proposal and the definition of some possible metrics for their structural performance assessment. The aim is to provide a robust background and detailed state-of-the-art information for these novel structural systems, towards the development of standardised and reliable procedures for their mechanical and thermo-physical characterisation.

1. Introduction

Contemporary architecture, emphasising lightness and transparency, brings a number of challenges for design, construction and operations, especially in the case of facades. Thermal prerequisites, as well as sustainability and energy efficiency technical requirements voted to reduce the operating costs of new constructions, lead to the design of adaptive facades, which are expanding more and more. Such an 'adaptivity' can take several forms, including local kinematics solely for shading systems, or more complex dynamics (see for example Fig. 1).

Compared to traditional curtain walls and envelopes [1], novel skins can be designed to respond to free-form motivations, or can be the result of production technology advancements [2–7]. Such innovation in design are generally aimed at improving the indoor environmental quality, and at facilitating the exploitation of renewable energy sources at the building scale [8], and can involve novel / smart materials, or an extension of specific principles (like transegrity, or bio-mimetic and nature-based concepts) to building enclosures (see [9–15], etc.).

Adaptive building envelopes can be considered, in this regard, the next big milestone in facade technology because they are able to interact with the environment and the users in several ways, by reacting to external conditions, thus adapting their behaviour and functionality accordingly. Nevertheless, facades represent the physical separation of indoor and outdoor, and thus provide protection of the occupants even under extreme events [16,17]. Therefore, besides architectural, functional and energy related aspects, adaptive facade systems must also meet fundamental requirements related to structural design, such as safety, serviceability, durability, robustness, performance under fire, etc. Many of these requirements are enforced by legislative procedures within the European Economic Area (EEA), lawful technical regulations

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[*] Correspondence to: Department of Engineering and Architecture, University of Trieste, Piazzale Europa 1 (building C9), 34127 Trieste, Italy.
E-mail address: chiara.bedon@dia.units.it (C. Bedon).

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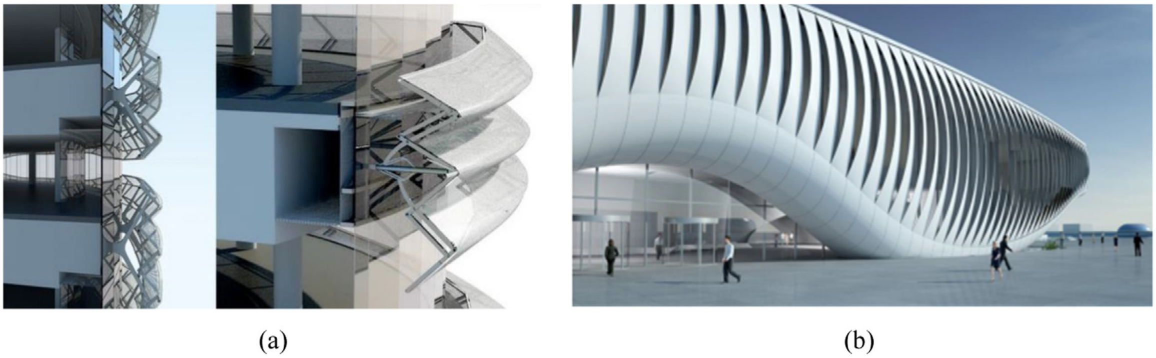
(a) (b)

Fig. 1. Examples of constructed adaptive facades: (a) CJ Cheiljedang R&D center, Seoul, South Korea (adapted from [18]) and (b) One Ocean Pavilion, Yeosu, South Korea (adapted from [18]).

and design standards, i.e. the Eurocodes, for the design and testing of structural components and systems.

In this context, this paper aims to present a state-of-the-art information on the structural characterisation of adaptive facades, with a special focus on architectural glazing (see also Section 2.3 for a brief discussion on novel materials and trends).

Such an effort requires the definition of specific parameters and rules, as well as experimental performance indicators and regulations. In this regard, this first part of the paper focuses on design issues, including the definition of possible metrics. These topics are discussed within the framework and activities carried out by the ‘Structural’ Task Group (TG) of the European COST Action TU1403 ‘Adaptive Facades Network’ (2014–2018), see [18].

2. Definitions and structural aspects for adaptive facades

2.1. Background

Adaptivity of a facade can be interpreted in several ways, depending on the conditions to adapt to, but also on the ways the system adapts to them. Loonen et al. [19], for example, define adaptive facades as follows:

> *‘A climate adaptive building shell has the ability to repeatedly and reversibly change some of its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance’.*

According to recent literature efforts and real projects, facade adaptivity is mostly related to energy performance, thermal comfort aspects, Indoor Air Quality (IAQ), or visual and acoustic performances. Although, facade adaptiveness can be favourable regarding the structural behaviour of buildings. Some types of facade adaptability may influence the performance of the load-bearing structure and its internal forces. In addition, the load-bearing structure of the facade itself can also consist in an adaptable structure.

Soong and Manolis [20] presented a concept of active structure as one consisting of traditional static (passive) members to support basic design loads, and dynamic (active) members to extend the structure´s capacity in resisting to extraordinary dynamic loads. Active and passive members are combined and optimised to produce structural systems which can adapt to changing loading situations.

Sobek and Teuffel, later on, described in [21] the adaptive structures as systems able to respond to changing external conditions through the manipulation of internal forces, deformations, or the external loads. According to the authors, this can be done in the following ways:

1) manipulation of the external loads, i.e. by adapting the shape of the structure (passive systems). In a facade, this could be rotation of elements to minimise wind exposure;
2) manipulate structural parameters, i.e. to adapt material or element properties, such as stiffness, length or damping, to influence internal forces or deformations (active systems). In a facade, this could be adjusting prestress in response to the wind loading;
3) a combination of (1) and (2), hence resulting in hybrid systems.

In general, based on the discussion from Morales-Beltran and Teuffel [22], adaptive structures are those which can give a non-passive controlled response to (typically) earthquake and wind-induced motions. ‘Non-passive’ means that they rely on the use of external energy supply for the control action.

2.2. A new classification proposal from the TU1403 ‘Structural’ Task Group

The ‘Structural’ TG recently presented a novel classification approach for structural adaptive facades, where major aspects are summarised in Fig. 2.

According to the TG classification as presented in Fig. 2, three aspects are of key importance, namely represented by:

(A) Mode of system change,
(B) Type of activation system, and
(C) Triggering event / change initiation system.

Their features and effects (including possible combinations) should be properly taken into account at the design stage, since these are typically responsible for multi-phase configuration changes (even cyclic) during the whole life-time of a given facade.

2.2.1. Mode of change

The first main aspect of classification relates to the ‘mode of system change’ (A), regarding geometry and stiffness. Changes in geometry can take place as a form of rigid body movement or non-rigid deformation of facade components. Rigid body movements can be simple movements, i.e. translations and rotations, or a combination them; whereas non-rigid deformations can be classified as distortions and dilations. The geometrical changes typically result into some form of restraints, which need to be taken into account in design (especially in terms of connections and joint details). The stiffness change in facades is explicitly related to the adopted facade details. Accordingly, under design loads, the resulting deformations are a function of the given design itself. For instance, a specific joint detail could provide additional stiffness to a facade, when faced by a specific type/intensity of load, but offer a mostly different mechanical restraint under other design actions. This can be also the case of passive, semi-active or active actuators for the mitigation of constructed facilities and components from extreme events (see also Section 2.2.2).

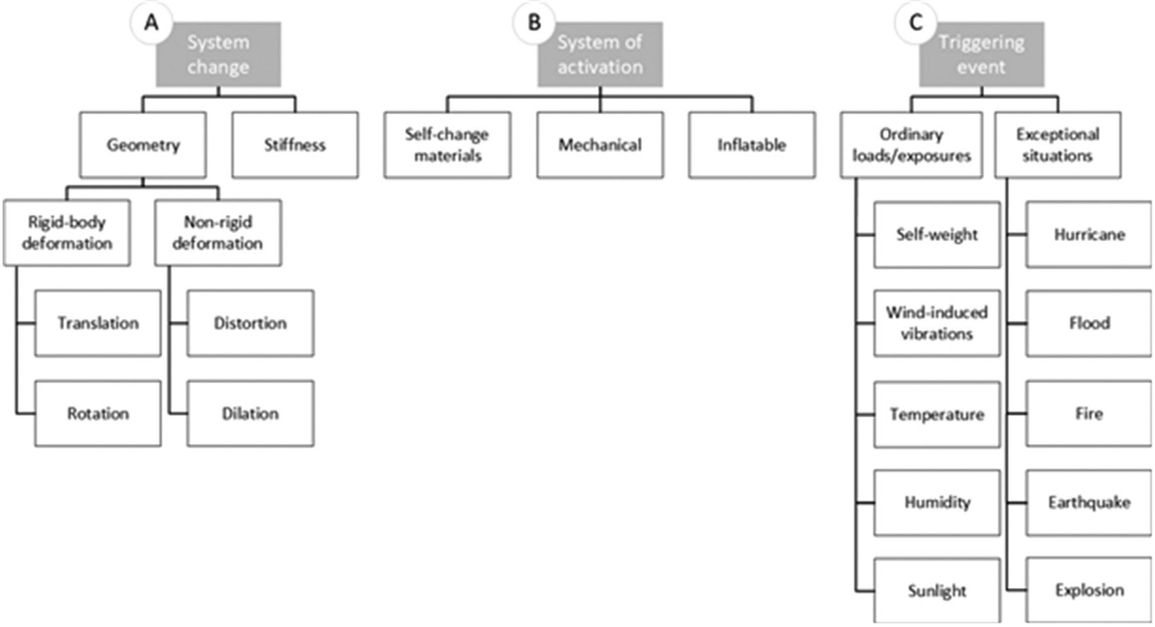

Fig. 2. Classification system of adaptive facades ('Structural' TG proposal).

2.2.2. *System of activation*

The second main aspect of the classification chart in Fig. 2 refers to the control system, namely denoting the 'activation type' (B), where the classification is carried out based on the underlying mechanisms governing the facade system's adaptation, such as self-change materials (i.e., thermo-sensitive materials like shape memory alloys, thermo-bimetals, etc.), mechanical actuators and inflatable systems.

Mechanical activation systems can be conventionally classified as active, semi-active and hybrid. If the control action is based on the introduction of large forces in the structural system, with heavy energy requirements, the system is defined as an 'active' control system. In a 'semi-active' control system, the control action is based on the modulation of a mechanical property within a given structural element (for instance magneto-rheological dampers), showing small energy consumption requirements. When several control approaches are featured at the same time, such a solution represents a 'hybrid' system.

The main objective of an automatic control system is to control a system variable (i.e. temperature, pressure, force, displacement), causing it to comply with a desired reference value. This variable is measured and controlled and it is called the controlled variable. Normally, the controlled variable constitutes the output of the system. The manipulation of the controlled variable is achieved by the system components through the variation, in a prescribed manner, of the actuating signal, also called the input signal. A control system that is able to feed the output variable back and compare it with the reference input, using the difference as a means of control is called a closed-loop control system or feedback control system (see Fig. 3).

Feedback control systems are not restricted to engineering applications but can be found in most biological systems in nature. The human body, for instance, is a highly advanced feedback control system. Both body temperature and blood pressure are kept constant by means of physiological feedback. In fact, feedback performs a vital function: it makes the human body relatively insensitive to external disturbances, thus enabling it to function properly in a changing environment. When a system does not have the feedback structure, it is called an open-loop system [27].

The main advantage of a closed-loop control system is that by using feedback it becomes mainly insensitive to external disturbances and internal variations in system parameters. It is hence possible, for instance, by using relatively inaccurate and inexpensive components like Micro-Electro-Mechanical System components (MEMS), to accurately control a structural system like a facade, whereas doing so is impossible in the open-loop case. An open-loop control system is easier to build since the stability of the system is not an issue. In closed-loop control systems, however, stability is a major problem since the system may tend to overcorrect errors and thereby causing oscillations of constant or changing amplitude. The controlled process is defined by the transfer function $G_{cp}(s)$ and the controller by the transfer function $G_c(s)$. The output $C(s)$ is fed back to the summing point, where it is compared with the reference input $R(s)$, yielding the actuating error signal $E(s)$. To modify the output in order to make it comparable with the reference input signal, a feedback-path transfer function, $H(s)$, is used. In this example, the resulting feedback signal is $B(s)$. More than half of the industrial controllers in use today are proportional-plus-integral-plus-derivative (PID) controllers combining proportional, integral and derivative control actions. The control signal is a linear combination of

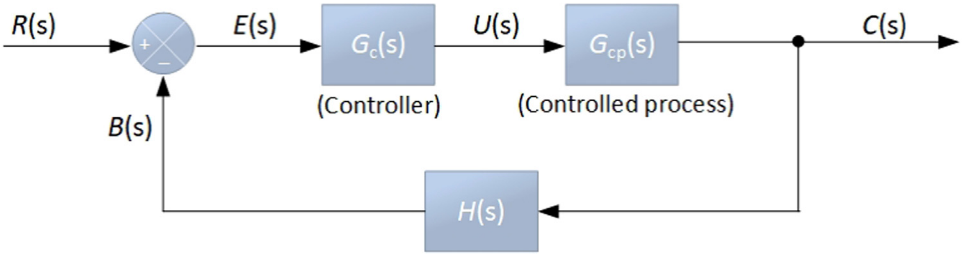

Fig. 3. Block diagram of a closed-loop control system.

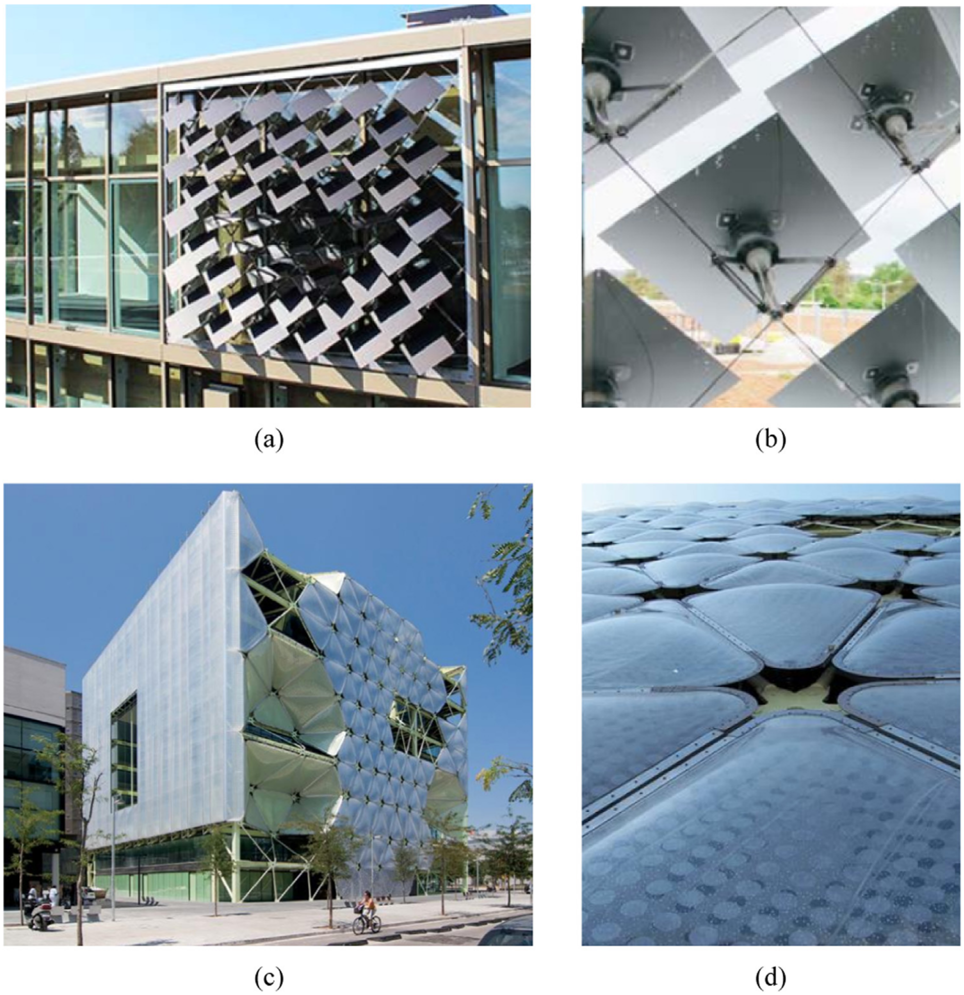

Fig. 4. Example of adaptive facades with pneumatic systems. (a) HoNR facade at ETH Zurich, with (b) detail of the actuators (adapted from [25] and reproduced with permission from Elsevier, Copyright ® license n. 4412500174098, August 2018); and (c)-(d) Media ICT building in Barcelona, Spain (reproduced from [26], Copyright ® Marysse, 2016).

the error, the integral of the error, and the time-rate of the change of the error. The usefulness of PID controls lies in their general applicability to most control systems, in particular to adaptive facades, and they prove to be most useful when the mathematical model of the structural system is not clearly known and therefore analytical design methods cannot be used.

In some cases, hydraulic solutions can be used, in the form of soft pneumatic actuators (see for example the House of Natural Resources (HoNR) facade at ETH Zurich, see Fig. 4(a)-(b) and [23,24]) or consist of full pneumatic chambers and air cushions (Fig. 4(c)-(d)). In both cases, inflatable facades should be separately investigated, since these are typically characterised - with respect to the other types of envelopes - by pressurized units composed of novel / unconventional materials whose performance should be properly assessed, in which both mechanical and thermal loads apply (i.e., load sharing phenomena in the air cavities, etc.).

2.2.3. *Triggering event*

The third classification aspect of the chart proposed in Fig. 2 focuses on the 'triggering events' (C), i.e. which event/scenario has initiated the activation leading to system changes. The possible scenarios - from a structural perspective - can be conventionally classified as ordinary loads/exposures and as exceptional situations. Ordinary scenarios are related to changes in gravitational loading (i.e., debris falling on the facade, panels disengage), wind induced changes (excessive vibrations/gust), temperature changes, varying relative humidity or sunlight. Exceptional situations are those which are unlikely to happen, but if they do, a response from the facade could mitigate some risks associated to these events. The events could be related to i.e. natural hazards such as extreme winds, flooding, earthquake etc. or technological hazards i.e. fire or explosions. The scenarios of interest for the full life-time of the structure should be properly evaluated.

2.3. *Traditional and novel materials*

Within the full characterisation of adaptive facades, special attention must be paid for materials. In modern buildings, facades typically include a large number of glass elements, and in most of the cases they take the form of wide glazing components to cover large spans [1]. In operational conditions, the glass components have to sustain specific thermo-mechanical restraints, by interacting with supporting members that can consist of steel, aluminium, timber, Fiber-Reinforced Polymers (FRPs), etc. It is generally recognised, in this regard, that glass as a building material plays a key role in the construction of facades [1]. The structural performance of traditional envelopes having various features attracted in the last years several research investigations, at the material, component and assembly levels (see for example [17,28–35], etc.). As far as these conventional materials are used for dynamic skins rather than static facades, major structural design issues are expected to derive from their thermo-physical and mechanical performance under

Fig. 5. Example of adaptive facade proposals. (a) Thin glass panels for flexible adaptive facades (figure reproduced from [41], Copyright @ Ribeiro Silveira 2016). (b) Prototypes of responsive cladding modules made of wood (wet and dry conditions; figure reproduced from [45], under the CC BY 4.0 Creative Commons Attribution License).

long-term and/or cyclic loads, including fatigue phenomena, material degradation due to environmental conditions, temperature variations, etc. Specific studies are hence required for structural assessment purposes ([36–40], etc.). According to recent research challenges, adaptivity and flexibility in facades can be achieved by means of innovative use of conventional materials, like thin glass panels allowing for cyclic deformations (see for example Fig. 5(a) and [41,42]).

In the last two decades, moreover, the design trend for dynamic facades is moving towards the combination (or partial substitution) of traditional building materials with novel solutions, that can be basically divided in several classes of materials, depending on their source of activation, allowable movement, source of natural inspiration (see an example in Tables 1 and 2). The increasing use of 'smart' materials in the field of architecture mainly depends on their ability to change their shapes and characteristics, under the influence of external stimuli such mechanical forces, electrical power, but also humidity, temperature, solar radiation, light, air movement and pollution, etc. In most of the cases, beside the architectural design goals, the main objective is related to sustainability, energy performance and thermal comfort optimisations [43–52]. Adaptivity can also derive from a novel use of conventional materials like wood (see for example [45,46] and Fig. 5(b)). The final result, for all these possible solutions, takes the form of so called 'responsive' facades, derived from bio-mimetic principles. Several research studies already proved the potential of these novel classes of materials [43–52]. On the other hand, literature projects also highlighted that the design of complex systems like adaptive bio-mimetic facades still requires efforts, and the application of biomimicry concepts must be further explored [52].

Table 1
Examples of smart and adaptive materials for facades (selection from [52]).

Class of materials	Conventional activation	Material	Activation
Smart	Energy	Glass-Fiber Reinforced Polymers (GFRPs)	Mechanical force
		Fiberglass-Reinforced Plastic	
		Polypropylene sheets	
		Shape Memory Alloys (SMAs)	Heat source provided by electrical current
		Elastic Polymer Materials with SMAs	
		SMA wires	
		Shape Memory Polymers	
		Thermoplastic resin matrix, reinforced by SMAs	Heat source provided by solar radiation
		Electro-Active Polymers (EAP)	Electricity
Adaptive	Environment	Thermo-bimetals	Temperature
		Heat sensitive plastics	
		SMAs	
		Thermochromic polymers	
		Phase Change Materials (PCM)	
		Phosphorescence pigments	Light
		Light responsive polymers	
		Photocromic dyes	
		Wood (beech, European maple, cut veneer)	Humidity
		Hydrogel	
		Carbon dioxide responsive polymers	Carbon Dioxide
		Titanium dioxide	

When these novel materials are used in complex facades (even for secondary components, shading systems, details, etc.), their performance should be properly assessed, as they influence the overall dynamic movement of the facades/assemblies. Actually, one of the major challenges is such that the structural and thermo-physical properties of these materials must remain stable in their different configurations to generate movement or kinetically adapt (in real time) to environmental changes, or variable restraint conditions.

3. Design concepts and goals for adaptive facades

3.1. General principles

One of the most essential functions of building envelopes is to provide shelter for occupants and users against both natural and man-made hazards. This function, as other structural components of a building, requires the consideration of structural aspects, such as safety, serviceability, robustness and durability (EN 1990 [53]). The first aspect concerns minimizing the probability of structural failures, which have both life-safety related and economic consequences. Rational minimum reliability levels (targets) have therefore been determined for various consequence classes. The verification of structural safety includes circumstances or conditions that the structure might experience during its life. Serviceability refers to the functioning of the structure under normal use, the comfort of people and the appearance of the building. Robustness refers to the ability of a structure to withstand accidental events such as explosions, fire, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause. Durability is the ability of a structure to maintain its performance during the design working life.

The Construction Products Regulation (CPR) provides a general regulatory framework for the performance of construction products in Europe [54]. The document provides essential requirements for construction works as a whole and in their separate parts, namely consisting of:

a) mechanical resistance and stability;
b) safety in case of fire;
c) hygiene, health and the environment;
d) safety and accessibility in use;
e) protection against noise;
f) energy economy and heat retention;
g) sustainable use of natural resources.

These aspects might influence the conceptual development of facades, especially if they are adaptive, i.e. respond to changes in their environment. Nevertheless, the requirements to address these aspects are provided by structural design codes, which should be fulfilled to ensure an adequate reliability against structural failure.

It should be mentioned that if a construction product meets CPR performance requirements, it does not mean that it fulfils the respective building regulations applicable for the construction project. In Europe, the national building regulations typically refer to and include some guidance on the application of Eurocodes, i.e. the European structural design codes concerning various structures, construction materials and design situations. The facade developer and designer must understand

Table 2
Examples of bio-inspired materials for facades (selection from [52]).

Class of materials	Source of inspiration	Material	Allowable movement / main features
Bio-inspired	Plants	Bird of paradise flower (*Strelitzia reginae*)	Elastic
		Waterwheel plant (*Aldrovanda Vesiculosa*)	Reversible snapping
		Flower of *Lilium Casa Blanca*	Unidirectional motion at the periphery
		Mimosa pudica	Touch and vibration sensitivity, folds inward as a reaction to contact
		Salvia officinalis	Passive changes of temperature levels
	Animals	Dung beetle, desert lizards, scorpions	Anti-wear surfaces
		Gecko, soil-burrowing animals	Smart adhesives
		Culex pipiens mosquito	Anti-fogging surfaces
		Owls	Noise reduction
		Stenocara beetle	Water capturing
		Moth eye, sea mouse, peacock feather, Paradise whip-tail	Optical functions

how the various requirements and regulations are organised in a complex structure.

Concerning structural performance, the EN 1990 [53] describes the basic principles and requirements for safety, serviceability and durability of structures, based on the Limit State concept. The verification format uses partial factors, to offset characteristic values representing various design parameters related to loads and resistances, and thus ensures that reliability targets are fulfilled. Following the provisions of the Eurocodes results in building components which have an adequate reliability against failure. Concerning the structural integrity of the entire building, additional measures need to be taken to provide appropriate robustness should one of the components fail.

It is important to consider that even if facade elements are not necessarily part of the main load-bearing structure, they could have a significant effect on the overall structural behaviour, i.e., moveable parts of a facade can influence internal forces due to wind action. Thus, the adaptability of facades might need to be considered i.e. when determining loads and structural response in terms of internal forces, stresses, strains or dynamic effects, etc.

3.2. *Requirements for facades*

Building envelopes are commonly required to resist self-weight, environmental actions (i.e. thermal effects and wind load), natural (i.e. earthquake) and man-made (i.e. impact and explosion) hazards. Moreover, structural design of adaptive facades must resolve structural consequences due to adaptive / movable systems, together with structural and cost consequences for the supporting substructures. Wind loading, for example, is a highly dynamic phenomenon and therefore a very interesting driver for adaptive architecture. Actuators of adaptive facades can also significantly affect dead loads to account for design: mechanically driven kinematic systems will lead to heavy complex construction components, while lightweight shape morphing elements are possible to construct with smart materials [55].

For building envelopes and components, structural criteria are specified at different levels: general harmonised conditions for construction products in Europe (EU 2011), national building standards (EN 1990) and recommendations from facade organisations (CWCT 2018). The most general regulatory framework for the performance of all the building products in Europe is represented by the Construction Products Regulation (EU 2011). It specifies basic requirements for construction works, namely related to mechanical resistance and stability, safety in case of fire, hygiene, health and environment, safety and accessibility in use, protection against noise, energy economy and heat retention, sustainable use of natural resources. The EN 1990 document defines then the conventional requirements for safety, serviceability and durability of structures, including regulations for the design, verification and reliability of structural systems. While inclusive of reference design loads for structures; however, the EN 1990 does not account for specific aspects of facades and envelopes, and moreover should be used in conjunction with specific standards related to fire design, accidental situations (i.e., earthquakes) and execution. The Centre for Window and Cladding Technology (CWCT) is an example of an industry funded centre providing more specific performance criteria for facades. It publishes both standards and guidelines developed together by leading architects, consultants, contractors and manufacturers.

4. Metrics and key performance indicators for facades

In building engineering, 'metrics' are conventionally assumed to represent, for facades and envelopes, specific performance parameters that are strictly related to the thermal comfort, energy performance and lighting response of a given cladding system with respect to the whole building. In the last years, the increasing development of adaptive systems attracted the attention of several research studies. Compared to 'static' performance metrics for thermal and lighting assessment of facades (i.e., U-value, g-value, daylight factor, etc.), a series of 'dynamic performance metrics' have been proposed in the literature (see for example [56–58]), so as to properly capture and optimise the expected behaviours, towards enhanced sustainability and comfort levels.

4.1. *Traditional facades*

Structurally speaking, the overall performance of a traditional facade is conventionally optimised - under the assigned ordinary design loads (i.e. self-weight, wind, or other live loads due to crowd, etc.) - so as to accomplish specific deflection values in service conditions (M1), that should be implicitly accounted for appropriate resistance performances of the load-bearing components. The same deflection limits, at the same time, are generally recommended by design standards so as to provide reasonable comfort for the building occupants (i.e., limitation of perceived movements and minimisation of potential failure risk). Another key structural performance parameter to account for in the design is represented by the weight (M2) of the structural (and non-structural) components. A series of additional (and more specific) performance metrics can then be defined and accounted for the optimal design of a given facade typology, especially adaptive facades. Horn [59], for example, focused on the design of truss facade structures and emphasised how 'structural performance metrics' can be merged and related to 'buildability metrics', so as to enhance their cost and efficiency. In doing so, Horn [59] proposed six additional metrics, namely related to (M*i*) a standardised length for the facade members, (M*ii*) trucking requirements, (M*iii*) number of structural connections to build on-site, (M*iv*-M*v*) structural joint geometry and connectivity, (M*vi*) variations in the cross-sectional features of the load-bearing components.

4.2. *Proposals and considerations for adaptive facades*

The current lack of specific regulations and guidelines to standardise the load-bearing mechanisms and performance of adaptive facades represents one of the major issues for their optimal design. Differing from traditional static facades (namely consisting of regular structural schemes), the variability in possible kinematic effects, materials (and related properties) and morphology (including free-form facade systems), does not facilitate the possible grouping of adaptive facade systems by boundary conditions.

Given the intrinsic features of adaptive facade systems, however, both the M1 and M2 metrics discussed in Section 4.1 can be reasonably considered as reliable performance parameters. The M2 minimisation, in particular, is herein recommended especially in presence of kinematic mechanisms involving rotations and torsional effects, that could induce fatigue phenomena. The trouble arises indeed in terms of deflection limit values (M1), since static facades are required to satisfy specific deformations that are strictly related to their loading and boundary condition (i.e. curtain walls, cable-supported facades, etc.). In this context, lateral deflection limits in adaptive systems should be generally related to the involved shape change and joint detailing, being responsible for local and global stress peaks that can be hardly controlled via standardised reference values. For preliminary estimations, the limit of 1/100, pertaining to the bending span, could be taken into account for adaptive facades. Although experimentation and / or numerical modelling can provide further support and feedback to design, lateral deflections should be related to stress peaks in the structural components so as to ensure (depending on the used materials) minimum stress-to-resistance ratios in operational conditions (limit values to define for each class of materials) and sufficiently wide safety levels.

Given the intrinsic features of adaptive systems, (M3) vibration controls are then recommended as a potential key performance indicator for optimal structural performances. According to the EN

1991–1-4:2005 provisions [60], for example, glazing facades and roofs with natural frequency lower than 5 Hz (i.e., condition that typically occurs for glazed spans smaller than 3 m) should be properly verified against vibration effects, even due to ordinary wind pressures.

Lastly, special care should be taken towards (M4) fatigue phenomena. In this case, specific probabilistic studies based on fatigue effects strictly related to boundaries, loads and materials are required for each facade type. In addition, no standardised design methods for fatigue assessments are available for (even static) facades, being explicitly calibrated in the literature - in most of the cases - for bridges under vehicle loading. Nakagami [61], in this regard, proposed a new method to account for the loading cycle of wind pressures in traditional glazing envelopes. The research investigations highlighted that such a probabilistic method can be very effective when the resonance component for a given facade system is relevant, compared to the assigned load wind spectrum. Extended analyses should be however carried out, for adaptive facade systems.

5. Summary and conclusions

In this paper, an insight on novel adaptive facades was reported, with special care for the structural performance assessment of these smart envelopes. Although adaptive facades are getting gradually more common in modern building skins, their design still represents a challenging task. Major issues are related to the structural characterisation, even in lack of specific design regulations and provisions in support of engineers. Differing from traditional cladding systems, the multiple ways in which adaptive facades can interact with the environment - and change their intrinsic mechanical and/or thermo-physical features - need to be properly taken into account. In doing so, basic definitions and methods should be firstly detected and shared among the design and research community. Then, specific experimental methods, regulations and performance indicators should be properly considered. The first part of the paper, herein discussed, focused especially on the state-of-the-art background and the design methods of novel skins. Later on, the second part of the paper was intended to mainly focus on regulations for experimentation, including testing approaches and recognised facilities, towards the definition of standardised procedures for still innovative but increasingly constructed dynamic facades. In doing so, major research outcomes from the 'Structural' Task Group of the European COST Action TU1403 "Adaptive Facades Network" were also briefly summarised in the paper, so as to provide further supporting information and to facilitate an optimal development of adaptive systems in buildings.

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