Evaluation of Adaptive Facades: The case study of Al Bahr Towers in UAE

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The evaluation of adaptive facades presents a challenge because there is no established evaluation strategy to systematically reach this goal. Many of the available façade performance evaluation systems or frameworks have limited applicability for such advanced building facades. The complexity of adaptive or dynamic facades...
evaluation is related to the performance evaluation of façade elements, systems and overall building performance coupled to occupant behavior and occupant satisfaction. In this context, we present a case study for an adaptive sunscreens façade and evaluate its performance and occupant behavior. The evaluation focuses mainly on pre and post construction phase of adaptive facades: The design assist phase (including the durability test, visual mockup, onsite mashrabiya mounting and weather stripping), the commissioning phase (field verification and performance testing) and the monitoring phase. The selected project is a 150 meters high twin tower that stands with honey-comb inspired structure and automated dynamic solar screen that responds to the sun’s movement. These solar screens respond dynamically and automatically to the angle of the sun which improves the control over energy consumption, solar radiation and glare with the ability to admit natural light into the building. The paper is part of the research activities of working group 3 of the European COST Action 1403 on “Adaptive Facades”. Different methods were used for evaluation, this include: interviews with the architect and façade engineer and technical control specialist, occupants, reviews of standard and codes, review of energy models and a systematic design process mapping. A documentation of the case study describing the post construction occupant comfort, and façade operation was prepared. This paper’s audience is mainly project managers, architects, building façade engineers together with facility managers concerned with the process of design, construction and operation of adaptive sunscreens facades. The outcome of this study identifies quantifiable performance indicators and effective strategies for the design and performance evaluation of optimal adaptive facades.

Keywords: sunscreens, occupant behavior, occupant comfort, solar gain, daylight, operation and control, service life

1. Introduction

In a world confronting environmental challenges, there is an earnest requirement for dynamic building envelopes that reacts to climate in an ideal way giving the best comfort and indoor environmental quality, while keeping up high effectiveness. Adaptive façades can give step-change upgrades in the energy efficiency and the use of renewable energy while improving the comfort of buildings tenants. In this manner, they are vital in accomplishing Europe’s 2020 targets (Annunziata, Frey, and Rizzi, 2013). Adaptive Facades are building envelopes that can adjust to changing climatic conditions on every hour, day, season or yearly basis. By adaptive we mean the capacity to react or profit by outside climatic conditions to meet productively and more essential successfully inhabitant’s comfort and well-being necessities (Luible, 2014). Adaptive facades are multi-parameter high performance envelopes that, inverse to static curtain walls, respond mechanically or chemically to external climate dynamically to meet inside loads requirements (cooling, heating, lighting or ventilation) and occupants needs (Loonen, Trčka, Cóstola, and Hensen, 2013).

Numerous already realized projects of adaptive building envelopes are constructed or are in the initial stage. According to the Climate adaptive building shells CABS database, which has been continuously updated, there are at the moment more than five hundred examples of buildings with adaptive facades (Loonen, 2013). However, detailed analyses data on the performance and design and construction process of those facades is not commonly available. Commissioning and construction verification details and performance data about adaptive façade's monitored operational performance and post occupancy evaluations are lacking in literature (Attia 2016, Boake 2014 and Karanouh, A. & Kerber, E. (2015)). Currently, European research in the field of adaptive building envelopes is coined by numerous nationally funded projects. Among those projects that aim to create a knowledge transfer between the individual research institutes amongst each other and the industry is the COST Action TU1403. The initiated COST Action TU1403 “Adaptive Facades Network” aims to pool together the knowledge, technologies and research from across European countries and beyond. The initiated COST Action TU1403 was started in 2014 and will run for four years. Currently 26 COST member countries plus Liechtenstein, China and Australia are involved in this COST Action with more than 80 participants from research institutions and industry (Luible, 2015). The main objective of this action is to harmonize, share and disseminate technological knowledge on adaptive facades at a European level. This shall lead to increased knowledge sharing between European research centers and between these centers and industry, the development of novel concepts, technologies and new combinations of existing technologies for adaptive facades, as well as the development of new knowledge such as effective evaluation tools / design methods for adaptive facades. As part of Workgroup 3, we are willing to address challenges and identify the gaps in the systematic assessment and operation of such solution, both in terms of
commissioning and operation, though literature review and mapping analysis (Attia et al. 2015a). In this context, we decided to investigate the adaptive façade of 150 meters high twin towers, with unique honeycomb-inspired structure with an automated dynamic solar screen.

Today there are a great number of façades and envelopes technologies that are readily available in the market. The decision as to how they are designed, operated, maintained and assessed remains a challenge. Our case study presented in this paper seeks better understanding of their design process, modeling and real performance. It will help illustrate the benefits as well as the challenges seen in specific solutions with respect to energy use, comfort, operation and maintenance. Currently, only a limited number of case studies have been documented (Attia 2016 and Boake 2014). This includes Al Bahr Towers in Dubai (Karanouh & Kerber, 2015), AGC Building in Louvain La Neuve (Samyn & De Coninck, 2014a) and the BIQ house in Hamburg (Wurm, 2013). The decision as to how they are designed, operated, maintained and assessed remains undisclosed and this in turn affects the wide expansion of adaptive façades. The paper is part of the research activities of Workgroup 3 of the European COST Action 1403 on Adaptive Facades, which is mainly concerned with the adaptive façades system design and assessment. The work group is look to understand how adaptive façades were designed and assessed during the major project delivery phases:

1. Predesign and Design Process,
2. Schematic and Conceptual Design,
3. Design Development and Construction,
4. Design Assist (pre-construction testing),
5. Commissioning,
6. Occupant operation (behavior) and
7. Post-occupancy evaluation and monitoring.

For this paper different research methods were used for the case study documentation, this include: literature review, site visit, interviews with the architect, façade engineer, glass manufacturer, commissioning agents, reviews of standards and codes and systematic process mapping. Within the scope of this study we present a case study description and technical details for the Al Bahr Towers Adaptive Façade. The case study provide significant insights on the design and construction process and the overlap between the glass product development and manufacturing and the building delivery process including mock ups and on site testing and verification. Section 2 starts with describing the research methodology followed of the present work. Section 3 describes the case study and discusses the main findings of the literature review. Section 4 presents the paper findings and results along three themes: (i) process mapping, (ii) interviews result and (iii) performance evaluation. Section 5 and 6 conclude the article with setting a list of learned lessons, by indicating some of the recommendations and key performance indicators that need to be addressed in order to guarantee a successful performance of adaptive façades.

2. Methodology

The goal of this work is describe in detail the process of design, construction and use of an adaptive glass façade – in this case Al Bahr twin towers – and evaluate its performance. As well as to propose a generic performance process map that could be used as a visual guideline support by companies in the building industry. First of all several existing documents were reviewed. Almost all Al Bahr Towers publications have been reviewed (Boake 2014, Cliento 2013, Karanouh & Kerber 2015, Linn 2014, Oborn 2013, Wood 2013) as well as the different standards and codes used for the building design and construction, this include: the CWCT (2006) Standard Test Methods for Building Envelopes. Secondly, a design and construction process map was developed. The development of such a map required more than a literature review. Indeed, the created map had to be validated and tested through life one to one interviews with different project stakeholders. Thus, this case study follow an iterative loop of development, test and review of information as presented below:

1. Extraction of the required information on actual integrated processes from the literature with a main focus on the three specific points (Steps, Roles, Tools).
2. Development of the maps of the design process based on the previous information.
3. Correction of the maps conceived in step 2 by conducting interviews with architects or engineers involved in Al Bahr Towers project.
4. Final discussion and recodification of the maps.
5. Then comparison with literature back to phase1.

To realize global and specific maps of the project delivery process the software MindMap was used. This software allowed drawing clearly hierarchical scales, task charges suite and information flows. To limit the scope of the process map we focused on the identification and modeling of generic processes that was associated with the Al Bahr Towers project delivery. The generic process identification can be generalized and used as a check-list to future designs of adaptive facades. Therefore, we focused on three main questions:

- The Steps: what series of phases an integrated process has to pass through and what are the determinant criteria for each step?
- The Roles: repartition on the responsibilities and scope of work, who must do what, how and when?
- The Tools: which software is used during the process and in what purpose?

Creating a process map involved systematic data-based interviews. Interviewees where asked to explain exactly what they did during the Al Bahr Towers project delivery, as well as share their technical challenges and express their expectations. For every interviewee a scope was defined identifying the parameters he or she was dealing with during the project. A technical drawing software program was used to visualize the process. After completing a first round of interviews, interviewees were asked for feedback (reviews) and confirmation to validate the process maps. Finally, a documentation of the case study describing the post construction occupant comfort and façade operation was prepared. The evaluation focuses mainly on pre and post construction phase of adaptive facades. We conducted several interviews mainly with the towers’ designer, Abdulmajid Karanouh, director of facade design and engineering as well as the technical control specialist.

The third part of the study address occupant satisfaction and thermal comfort of Al-Bahr occupants. Physical monitoring was not allowed by the building manager and the facility manager could not share any real consumption or comfort data. So we opted to use questionnaires for indoor environmental quality assessment. 22 employees responded to our online survey comprising multiple choice with one or more responses and short or long open answers (not exceed 10 minutes). The questionnaire was based on Annex ‘Thermal Environment E2 Satisfaction Survey’ of the standard ASHRAE 55-2010 norm and the Center of Built Environment standard questionnaire that seemed complementary (Attia, S., & Carlucci, S. 2015).

Fig. 1a) Northern Façade of Al Bahr Twin Towers, b) South façade, with some opened and closed shading devices, Coordinates: 24° 27′ 23″ N, 54° 24′ 4″ E, Alt: 3m. (Photo Courtsey: Terry Boake)

3. Case study

Abu Dhabi Investment Council is the investment arm of the Government of Abu Dhabi responsible for investing part of the government’s surplus financial resources. In 2008, the Abu Dhabi Investment Council launched an international competition for its new headquarter. The new headquarter is located on the north shore of Abu Dhabi Island, overlooking the Eastern Mangroves and towards Sadiyaat island and the Persian Gulf beyond. Therefore, the project name is Al Bahr ( ) which means the sea in Arabic. Abu Dhabi has a hot humid climate, extremely sunny with temperature and humidity reaching 49oC and 100% respectively during summer. Aiming to design two iconic towers, the design brief called for two 25 story towers to create an outstanding landmark reflecting the regions architectural heritage together with the cooperate status of the clients organization. The primary business functions of the towers include financial transactions, brokering and dealing including Al Hilal Bank. In the same time, the project brief requested a contemporary sustainable building using modern technology without setting any performance or certification requirement.

3.1. Concept

The project concept is inspired by traditional Islamic object the ‘Mashrabiya’ ( ) and motifs to stand out with two circular towers covered by honeycomb-inspired structure and its automated dynamic solar screen. The ‘Mashrabiya’ is a wooden lattice screen found in traditional Islamic architecture and used as device for achieving privacy and environmental control including natural ventilation, solar control and glare reduction. The project area is 56,000 square meters primary for office use (Bank). The design submitted by architect Abdulmajid Karanouh (AHR/Aedas) offers two 150 meters high circular towers clad with curtain wall covered with a kinetic shading system (Fig. 1a). The tower floor is open plan office spaces with service core. In some floor the space is divided into cellular offices and meeting rooms. Each tower hares a two-level basement with 24-storey office space that includes catering, auditoria, prayer rooms, gymnasium and plant rooms. There is a basement for car parking and secure vaults for banking services. Following an international design
competitions the client chose the striking concept submitted by a UK based multidisciplinary design team (AHR/Aedas/Arup). There is an entrance podium for both towers covered with a 100 m curved roof. The buildings is fully air conditioned with various back areas associated with storage and catering. Finally the project won the 2012 CTBUH Innovation Award. The project concept was placed second at the Emporis Skyscraper Award – the world’s premier event for high-rise architecture – for projects completed in 2012. The project has been featured on the Chicago-based Council on Tall Buildings and Urban Habitat’s “Innovative 20” list of buildings that challenge the typology of tall buildings in the 21st century.

3.2. The Envelope

The two circular towers are clad with weather-tight glass curtain wall. The curtain-wall is comprised of unitized panels with a floor-to-floor height of 4200 mm and a variable width of 900 mm to 120 mm. From floor to ceiling the vision area of the curtain-wall spans 3100 mm. The curtain wall is separated from the kinetic shading system through a substructure by means of movement joints. The fixation of the substructure movement joints (cantilever struts) is at the first basement, ground floor and podium levels to allow them to behave independently from the substructure. The dynamic shading system is a screen comprised of triangulate units like origami umbrellas. The triangular units act as individual shading devices that unfold to various angles in response to the sun movement in order to obstruct the direct solar radiation. Each Mashrabiya was conceived as a unitized system cantilevering 2.8m from the primary structure. The shading device system has stainless steel supporting frames, aluminum dynamic frames, and fiberglass mesh infill. The folding system transforms the shading screen from a seamless veil into a lattice-like pattern to provide shade or light. Each shading device comprises a series of stretched polytetrafluoroethylene (PTFE) panels. When the shading device is closed occupants can still see through from inside to outside (see Fig. 2). In total each tower has 1049 Mashrabiya shading devices, each weighing about 1.5 tonnes. The shape of the building in plan and elevation led to 22 different variations in the Mashrabiya geometries, which in itself created a challenge for managing their manufacture and assembly.

Fig. 2a) three fully opened shading device allowing view during non-solar times, b) a group of shading devices fully opened (Photo Courtesy: Terry Boake).

3.3. Automation and adaptions

The shading screen is computer-controlled to respond to optimal solar and light conditions. The Mashrabiya shading devices are grouped in sectors and operate through sun tracking software that controls the opening and closing sequence according to sun angle. Each shading device comprises a series of stretched polytetrafluoroethylene (PTFE) panels and is driven by a linear actuator. The actuator is responsible to open and close once per day based on a pre-programmed sequence to prevent direct. In the case of overcast conditions or high winds a series of sensors integrated on the building envelope will send its logged signals to the control unit to open all units. The Fig. 3 shows in detail the individual shading device with the actuator, sleeves, arms and fabric mesh.

Fig. 3) Detailed 3D model of an individual shading device (Courtesy Wood, A. (2013).

Fig. 4a) A close photo of the Mashrabiya and curtain wall where the strut sleeves penetrate the curtain wall and connect to main strucutre, b) View out while Mashrabiya is open (Photo Courtesy: Terry Boake).

4. Results

Several interviews have been conducted to identify exactly the roles of the project’s main stakeholders in different stages. This included the architect, energy consultant, building’s users, adaptive glass façade subcontractor, shading system manufactures, commissioning agent and the facility manager. The key steps of the adaptive facades delivery process are identified including decisions, checklists and teams engaged in each stage respectively.

One of the most significant findings related to this project was that the client required a “sustainable office building” similar to Northern or Western type of concrete and steel structures with a panoramic glass façade similar to mainstream offices that you find in the Gulf Countries. Surprisingly, the project did not get certified by any LEED rating system and Arup modified its reporting to state that the project is designed in accordance with the US Green Building Council LEED rating system instead of stating that the project failed to get certified.

4.1. AGC Building Project Stakeholders and Process Map

The process mapping was completed by interviewing seven project stakeholders representing, the façade
contractor, architect, general contractor, energy and building physics consultant, commissioning agency, and facility manager. Figure 5 shows the results of the interviews and represents the different stakeholders of the project. The process map, shown in Figure 6, indicates that there were seven major design stages in this project, named according to the AIA (AIA, 2007). The figure shows the process map after being validated, illustrating the design and construction stages of the adaptive façade as a whole.

Fig. 5) General composition of Al Bahr adaptive façade team.

4.2. Façade Design Process Description

The interviewees revealed that Al Bahr towers delivery process went through an iterative process with experimental validation approach. The iterative approach did allow a holistic integrated and iterative approach. The project went through twelve stages:

1. Competition with the dynamic Musharabeya Concept (Abdulmajid)
2. Setting Design Team, (AEDAS+Arup)
3. Submit the project (July 2007)
4. Wining the competition (Nov 2007)
5. Assembling a design team (70 architects and 150 engineers (structure, MEP, Fire etc.) + Design Development and Construction Documentation
6. Tendering and Contractor Selection
7. Mock-ups
8. Benchmark (see Figure 7)
9. Construction
10. Occupation
11. Commissioning
12. Soft Landing

For example, the glass was selected through material identification session to support the glass box concept for the nearly zero energy targets prior to the identification of the mechanical, thermal and visual performance of the glass. Thus, the selection of the façade glazing was mainly based on aesthetical reasons during the schematic design phase. The glass façade comprised three layers namely, the primary (internal) curtain wall, the steel structure and the automated glass sunshades. The most critical layer of the façade was the third layer with external automated sunshades. This layer had multi-functional and multi criteria performance requirements including glass transparency, color, weight, size, solar energy transmittance (g-value or SHGC) and movability. However, the project delivery process forced the architect to select the louvers based on their transparency and color neutrality. Later on, the energy and building physics consultant had to optimize the glass louvers to avoid glare and overheat when the louvers are set to block the sun. The energy and building physics consultant had to conduct several simulations models and experiment with a climate chamber and test bed in the Netherlands, to maximize the g-value and come up with a working prototype (see Table 4-6 and Figure 8). Thus, the façade design was detailed and validated in a late stage of the design process. This was until the façade subcontractor was invited, when the final façade system design decision was made. The involvement of the glass façade subcontractor at the end of the design process resulted into a complicated situation. Finally, a silk printed glass with a tempered mesh was finally proposed to address the mechanical, thermal and visual performance requirements. It would be optimal if the glass subcontractor was engaged during the concept development. However, the competition based approached hindered such an approach and kept the responsibility in the hand of the architect. Therefore, it is very important to engage the façade engineers from the beginning of the design to guarantee hands on feedback and follow the shortest and the most cost effective design path.

To ensure proper coordination between the various building components a digital model guaranteed the coordination and integration between the concrete core, the structural steel frame, and the Mashrabiya.

Fig. 6) Process mapping of the integrated design process of the AGC glass building’s adaptive façade (For a higher resolution version please follow this reference (Attia 2016).

4.3. Façade Assessment Process Description

Most of the façade testing took place offsite. The project had a limited budget in relation to the project size. The design team had to rely on simulation tools and CFD analysis. Then static mock-ups and the mechanical mock-ups were put on hold. It was important to set up a visual and kinematic mock-up first. Also a series of
wind-tunnel test were conducted at various scales. The fluid form of the building lead to a low positive and negative pressure during the testing, averaging 1.5 kPa up to a maximum of 3.5 kPa. The façade contractor was responsible for three mock-ups:

1. Onsite mock up for fabric testing,
2. Lab tests in Switzerland (Yuanda Basel) in a special chamber to test the mechanics for 30,000 cycles (humidity 100%, 65 Celsius and sand mixed with salt). The shading devices had to be tested to operate with a high reliability and robustness. The shading devices are prone to wind-induced movements and aggressive environment containing sand, dust and salt-laden air. A series of prototype test on the PTFE panel were conducted at both ambient laboratory and elevated temperatures to the check the required durability and life of actuators, bearings, and mechanism overall.
3. Mock-up in China for lighting (Shenyang Yuanda). Then a benchmark was set up on site.

The façade assessment and commissioning was mainly on the hand of façade subcontractor. There were serious issues with commissioning the building façade. It was supposed to have a third party commissioning company but it was done finally by the façade sub-contractor after two years of operating the building. The process was under paid and had miss-representing professionals. In general testing and validation was under appreciated by the client when it comes to an adaptive facade. Regarding soft-landing, the late commissioning of the buildings postponed the soft-landing to (2015), the building was constructed in 2011 and opened in 2012. The project manager needed 24 months to do the soft-landing after occupation. The idea was to monitor the building for 12 month then effectuate changes and then measure again the results of our intervention to reach the optimal operation mode. However, only a 12 months monitoring was conducted in 2015. Occupant behavior of building users was identified and the deficiencies encountered during the summer and winter cycles were highlighted.

Fig. 8a) A full-scale prototype of the mashrabiya undergoing mechanical testing at Yuanda’s facilities in Shenyang (Aeadas Architects Ltd.). b) Onsite benchmark for 6 mashrabiyas (Karanouh, A. & Kerber, E. (2015)

4.4. Survey results

All respondents are working in zone 2 of the tower (office floors from 10-20). The initial survey results indicate, concerning thermal comfort, that 12% of occupants are very comfortable, 42% are comfortable, 32% are neutral and 10% are uncomfortable and 4% very uncomfortable. The main reason for discomfort was recorded by females mainly due to over cooling. For natural lighting the results are distributed as following: 20% are not comfortable, 40% very uncomfortable. At the beginning we thought that this is due to glare however, the main reason was related to the automated opening and closing of the mashrabiya. A large percentage of occupants stated that they are annoyed by the regular opening and closing of the mashrabiya not allowing them to interact with the façade. Despite the user controlled roller-blinds is provided to permit the occupants personal control of their environment they are kept most of the time open according to respondents. The automation is causing a widespread occupant discomfort which is accentuated by their passivity towards their indoor environment control. So far we consider this in its initial phase with a little representative number of 22 employees out of 1000 employees of the two towers.

5. Discussion and Conclusion

The primary objectives of this study were to present a detailed case study description of a building with an adaptive façade and to derive maps of the underlying decisions on how it was designed, operated, maintained and assessed. This study required time, effort and analysis to interview Al Bahr project key stakeholders. The required data interpretation and classification besides conducting interviews and surveys. The facility management company refused to cooperate in this study and did not share any performance data on energy consumption or comfort conditions. However, we succeeded to create sophisticated process map representing most stakeholders who participated in this outstanding project. For sure the project is an outstanding project from a design and construction point of view but not from a sustainability point of view. Therefore, and after this long endeavor we came out with some key learned lessons that can be considered in any future building with an adaptive external shading façade:

1. The project embeds a series of innovations and is a fruit of successful collaboration between the client, design team and builder. The mashrabiya concept and its implementation are ground breaking and the towers succeeded as an iconic landmark. The design team pushed the boundaries of design and managed to set new standards for quality in the AEC industry.
2. Another success of the design team was that their members identified the performance requirements for the adaptive facade. Without quantified performance indicators the project would not succeeded. Arup in particular has the vision, early on in the project, to develop the Mashrabiya Performance Criteria Development Guide and the Building Geometry Construction Manual. Both documents set new standards for the façade design and construction quality. The performance quantification resulted in a rigorous design assist phase with several models, mockups and prototypes testing. Both documents set up the specification of the façade performance with a focus on structural, mechanical and durability of the facades.

3. The use of BIM and parametric geometrical modeling was a crucial tool for the concept development and team collaboration. The use of building information technology and parametric modeling allowed the team to operate in an efficient, integrated and effect approach. The advanced computation design capacity of the design team (AEDAS + Gehry Technologies) allowed the building envelope development and the rationalization of the complex façade geometry including the curtain wall glass panels in a uniform and coherent manner. The use of Rhino Script to calculate the deflection limits of glass panels based on established algorithms rules was a key step to refine and optimize geometry. The glass panel optimization process lead to the elimination of custom manufacturing of glazing. Moreover, the paramedic advanced modeling was the key methodology to control the mashrabiya folding limits and generate precise shop drawings for implementation. The procurement of the building envelope under one contract was a reason to valorize the BIM model and empower the modeling team. Gehry Technology, who assisted AEDAS in generating the parametric models in Digital project and CATIA based tool during the design development phase was retained in the construction phase in order to guarantee compatibility while achieving the highest degree of standardization integration during construction.

The outcome of parametric modeling and analysis was integrated into one BIM model, which was the main red thread across the project unifying and integrating both the design and constructions teams. The construction phase had almost identical as-built drawing compared to the design development drawings. The coordination of work among various contractors, manufactures and suppliers in a seamless way with minimal class detection was BIM cause success.

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