DOI: 10.38027/ICCAUA2021165N10

Contemporary Adaptive Systems in Architecture and Structural Engineering: State of Art and Future Perspectives

***** Dr. **Yenal Akgün** [1]
Yaşar University, Faculty of Architecture, Izmir, Turkey [1]
E-mail [1]: yenal.akgun@yasar.edu.tr

Abstract
In all times of history, engineers and architects have searched for opportunities to develop adaptive structures, buildings and building parts, which are equipped for adjusting to ever-changing requirements and conditions. The reasons behind this interest relate to the growing need for functional/ spatial flexibility, sustainability and extended capabilities of structural performance. Recent advancements in construction technology, robotics, architectural computing and material science have increased the interest for these structures/ systems; and allowed us to develop examples that are more advanced. This paper aims to introduce the state of art contemporary adaptive systems in architecture and structural engineering; and presents a future perspective for these systems and their potential applications in the construction industry.
Keywords: Adaptive Structures; Deployable Structures, Adaptive Façades, Parametric Design; Smart Materials.

1. Introduction

In general, an adaptive system can be defined as a mechanical structure, building or a building part with the ability to change its configuration, location, geometry or physical properties in response to changes in the environment. Recently, after the development of the automation technologies, this definition has been changed to "the systems, whose geometric and inherent characteristics can be changed beneficially to meet mission requirements either through remote commands and/ or automatically in response to external stimulations" (Wada, 1990).

The concept of adaptation in architecture goes back to ancient times. Throughout history, architects have always searched for methods to design buildings and building parts that can adapt to ever-changing environmental, spatial and functional requirements. First ancestors of adaptive systems used for protection against environmental conditions were simple nomadic tents with flexible/ deployable skins (Tzonis & Lefaivre, 1995). Another example is the deployable fabric sheets used to cover the roof of the Roman Colosseum, which shaped sun shelters for the audience, providing shade as well as a breeze as they sloped down towards the centre to catch the wind (Zuk & Clark, 1970).

In medieval times, the concept of adaptation and flexibility in architecture did not lose its importance, and the ancestors of adaptive roofs, canopies and sunshades were used (Korkmaz, 2004). With the Industrial Revolution in the 19th century, modern design solutions and innovations were incorporated into architecture. New building materials such as cast iron, steel, and glass gave architects and engineers the freedom to construct buildings and structures of previously unprecedented scale, shape, function and of course flexibility (Schumacher, Vogt, & Krumme, 2019).

Technology became an increasingly important factor in facilitating architectural adaptation and innovation especially after the last decades of the 20th century. The developments in automation, computation and material science have also facilitated the applications of adaptive systems in architecture and structural engineering. Due to these developments, adaptive systems of the era have all started being integrated with sensors, control intelligence and actuators (Senatore, Duffour, & Winslow, 2018a). These systems also have a strong interaction with the physical environment and users. This interaction has created a demand for these systems; and with the growing interest in these systems owing to their improvements compared to conventional structures, different types of adaptive systems have been designed and applied by architects, engineers and researchers to meet the requirements of the users (Schumacher et al., 2019).

The demand for the adaptive systems in architecture and structural engineering seems to continue increasingly in the future. If structural and technological advances drive this trend and demand, we may be at a unique breaking point in the history of architecture: similar to the flying buttress or mass fabrication wherein technology is leading architectural aesthetics.

There are different types of adaptive systems in architecture and structural engineering. It ranges from media facades to sustainable smart buildings, from responsive digital art installations to stage designs and from artificial intelligence to automation systems and computing (Kronenburg, 2007; Schnädelbach, 2010). However, this paper only deals with the structural systems, building envelopes (roof and façades) and special structures that can change the spatial characteristics of the buildings. Other types of smart structures and systems are not in the scope of this paper. In addition, development on the chemical/ physical properties of the smart materials are again not in the scope of the paper.

The paper investigates the demand for adaptive systems in contemporary architecture and draw a future perspective in five sections: After a short information about the definition of the terms and importance of the topic, contemporary technologies and materials used for adaptive systems in architecture and structural engineering have been summarized. Then, contemporary examples of adaptive structures, façade and roof systems have been investigated in three groups. In the fourth part, future perspectives for the adaptive systems have been explained. Last section is for the conclusion and discussion.

2. Technologies of the Contemporary Adaptive Systems

Adaptive systems are also called smart or intelligent structures/ systems in the construction industry. The smartness and/ or intelligence comes from the responsive character of the systems to the changing environmental or architectural conditions, which is obtained by the integration of various sensors, control intelligence and actuators. Today, sensors, actuators and the control system are the basic components of an adaptive system. Sensors are responsible for monitoring the environmental changes and generating signals proportional to the changing measured parameters. Actuators partially or fully change geometry/ form/ position of the adaptive structure in order to obtain the desired response. Control systems constantly track the sensor's signal, interpreting the data to decide if action is necessary. If a response is required, a signal is sent to the appropriate actuator(s) (Özgen & Erdinç, 2017).

The most obvious need and driving force for the intelligent systems started with the aerospace, defence and automotive industries, but the construction industry has already exploited the ideas from these application areas in (Culshaw, 1992). Today, origins of many systems in architecture and structural engineering are taken/ adapted from the above-mentioned industries.

In structural engineering, adaptive systems has focused mostly on the control and optimization of loads, vibrations and stiffness for buildings or bridges to improve safety and serviceability during extra-ordinary high loads such as storms and earthquakes (Senatore et al., 2018a; Senatore, Duffour, & Winslow, 2018b; Soong, 1988; Soong & Chang, 1982). In architecture, intelligent systems are seen mostly on HVAC and façade/ envelope systems. With the increase of the demand for sustainable and smart building solutions and interactive façades, new materials and capabilities of the technologies are developing day by day.

When the literature on the topic is investigated thoroughly, it may be seen that there are many different methodologies to design/ control/ actuate an adaptive system. Some of these methods are based on the integration of actuators to the conventional structures/ systems; some require designing all structures/ systems according to the type and movement of the actuation; and some need special materials. Again, while some adaptive systems work without assistance of electronic controls or feedback systems, some have sensors and/or feedback systems to tune the response behaviour.

Active bracing systems are one of the most popular adaptive systems in structural engineering. In this system, different actuators (mostly hydraulic) are used as cross-bracings, which actively responses according to the loading conditions of the whole structure (Fateh & Hejazi, 2021; Golafshani, Rahani, & Tabeshpour, 2006; Loh, Lin, & Chung, 1999; Soong, Reinhorn, Aizawa, & Higashino, 1994).

Active cable tendons have also been used to change the amount of pre-stress in cable-stayed bridges, steel trusses and reinforced concrete beams to limit displacements under loading (Bossens & Preumont, 2001; Garrido, Curadelli, & Ambrosini, 2014; Guo, Lu, & Li, 2008; Jann-Nan & Fanis, 1979; Preumont, Achkire, & Bossens, 2000).

Actuation has been used to change the membrane stress state in shell structures that are typically constructed using shape optimization methods to achieve ideal geometry under constant load (Senatore et al., 2018b). To deal with the loads at extra-ordinary conditions, actuation in the form of induced strain or supportive displacement is used to minimum the maximal stress (Neuhäuser et al., 2013; Neuhäuser, 2014).

Active structural control is generally used in applications for shape control. In this system, type and amount of the movement of the actuator(s) defines the actual geometry of the whole movable building part (Gantes, 2001; Pellegrino, 2002). Many of the deployable/ retractable roofs and kinetic façade systems in the literature use this control method (Lewis & King, 2014).

Compliant structures, also known as compliant mechanisms, are versatile mechanisms that transmit force and motion via the deformation of an elastic body. The deployment of satellite antenna reflectors, the control of aircraft wings (Arena et al., 2017) and the control of direct daylight in buildings (Lienhard et al., 2011) have all been done with active compliant systems.

In addition to the abovementioned methodologies, use of smart construction materials are also important in the adaptive structures research area. Smart materials are those that have the capability to respond to changes in their condition or the environment to which they are exposed, in a useful and controlled manner. It is possible to summarize these materials as: Piezoelectric materials, shape-memory alloys, thermoresponsive materials, chromic materials, magnetostrictive materials (Addington & L.shock, 2005; Mekhzoum, Qaiss, & Bouhfid, 2020).

3. Contemporary Applications of Adaptive Systems in Architecture and Structural Engineering

Parallel to the development of computer technologies, computational design tools and smart materials, the interest in adaptive systems in architecture and structural engineering has increased for a few decades. The demand of the users and architects for more flexible and interactive spaces, components and structural systems has also supported this interest. From the user's perspective, adaptive building components bring the architectural design to the forefront of a visitor's attention. This interplay of technology and architectural experience can be viewed as a dialog of design and/ or interaction between engineering/ architecture and the societal context.

In addition to the aforementioned discussion, sustainability has also gained importance for a few decades and adaptive/ smart buildings create a response to this concept by providing important energy, material and cost efficiency in the long term. The hypothetical ideas, which could not have had a chance to be realized thirty years ago, have had a chance to come true today with the advancement in technology and change of design understanding. Adaptive buildings of this age do not require human assistance but respond naturally to the environment in impressive ways (Johnson, Zheng, Nakano, Schierle, & Choi, 2019).

When the contemporary examples of adaptive systems in architecture and structural engineering are investigated, it can be seen that the concept of adaptability varies from small-scale applications such as louvers/ sunshades that adjust to the sun's angle to big scales like entire roofs/ envelopes that deploy and change building form.

In this section of the paper, the concept of adaptability and its contributions to the architecture is investigated using well-known examples in three subsections as adaptability in structural systems, adaptability in architectural components that change the spatial quality of the spaces and the adaptability in building envelopes.

3.1. Adaptability in Structural Systems

Conventionally, our built environment is static and building structures of this environment are designed considering the worst situations/ maximum stress that they may face. This means, the cross section of a conventional building structure is always more than the needed sizes in ordinary situations. The expected/ foreseen hazardous situations are very rare and sometimes never happen during the lifetime of a building structure. Thus, we waste materials by this design strategy. Contrary to this understanding, one of the primary philosophies of adaptive building structures is to design the structures as light as possible and well prepared to the rarely seen dynamic loads through an active manipulation of the structure. Earthquake dampers and active bracing systems of skyscrapers are the typical examples for this design philosophy.

As one of the contemporary pioneering examples, adaptive cantilever truss developed by Gennaro Senatore (Senatore et al., 2018b) can be reported. This innovative truss example calculates the loading conditions simultaneously using active structural control method, and restrain the deflections at cantilever structure.

Stuttgart Smartshell is another important study on the topic as the world's first full-scale prototype of an adaptive shell structure (Figure 1). The 10m x 10m double-curved structure, consisting of a multi-layer wood laminate with a mere 4 cm thickness, has three freely positionable supports. Multiple sensors record the load status at numerous points on the wooden shell. The manipulation is achieved through hydraulic drives: within milliseconds, targeted movements of the points of support counteract variable loads and thus reduce deformations and material stresses caused by wind, snow and other loads (Neuhaeuser et al., 2013; Sobek, Bergmann, & Haase, 2012).

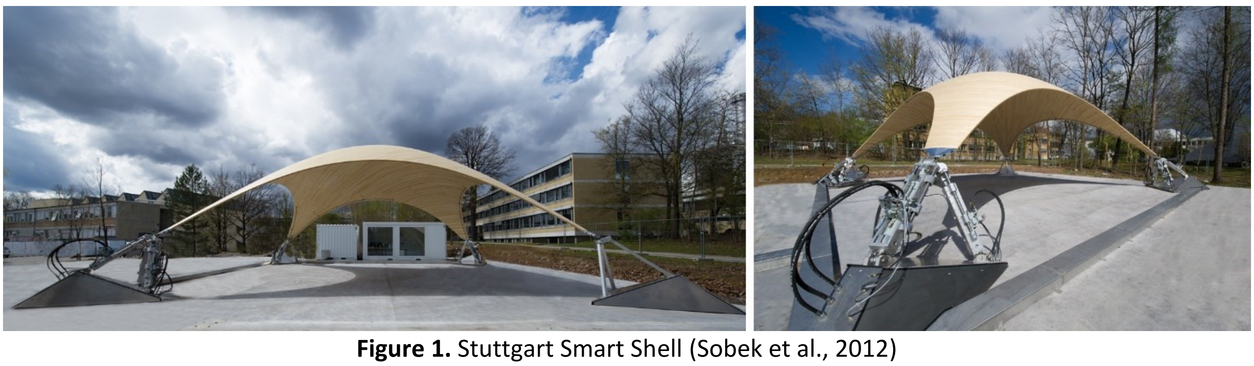

Figure 1. Stuttgart Smart Shell (Sobek et al., 2012)

Parallel to the studies on the active structural control with sensors and actuators, there are many deployable/ convertible/ foldable examples, which search for an adaptation via geometric transformation, as well. Creating a formal variation through structural transformation is often seen at bridges. During history, many well-known movable bridge structures have been designed such as the Tower Bridge in London and Kieler Hörn Bridge in Kiel. All these examples have only one active geometry and cut the pedestrian/ vehicle flow at their contracted or folded positions.

Contrary to this conventional approach, flexible scissor-bridge in Geneva, designed by Ingeni and MID Architecture (Figure 2), can be active at any positions, have emerged. On this four meters wide pedestrian bridge, the middle part is formed as a moveable jetty with scissor-hinge mechanisms. By this clever idea, the engineers and architects have created an innovative, unique bridge mechanism that clears all obstacles out of the way, for the problem with most moveable bridges is that they enable only one mode of traffic at one time: either foot traffic or river traffic (Schumacher et al., 2019; URL-1, 2017).

Figure 2. Jet D'eau Mobile Walkway (Schumacher et al., 2019)

3.2. Adaptability in Architectural Components that Change the Spatial Quality

Development on the adaptive system technologies has not only affected the structural engineering, but also the spatial/ functional characteristics of the buildings. Architects and designers of the era have realized that the buildings and/ or building components can interact with the user, or create multifunctional spaces for different uses at the same architectural space. As a result, a novel design conception/ design method, which is completely based on the adaptation, has emerged. In this method, architects and designers aim to design buildings that are flexible, interactive, multifunctional, sustainable, and future-proof rather than fixed, immovable objects that are stuck in a specific context and time.

This novel understanding has an important potential for the future of our planet, as well. It is known that the construction industry is responsible for almost 40% of the carbon emissions and attempts for multifunctioning or spatial flexibility and adaptability may decrease this ratio.

Stage designs of Gala Systems for different multipurpose halls (URL-2, 2021), such as SwissTech Convention Centre-EPFL (Figure 3) in Switzerland, Baku International Conference Centre in Azerbaijan, Kauffman Centre for Performing Arts in USA are good examples for this design understanding. Instead of constructing several flat and inclined halls for different functions, capacity and spatial qualities, these multipurpose halls change their geometry, capacity and height according to the number of the audience and necessities of the function. Thus, it is possible to obtain numerous functional alternatives in one hall and this situation creates remarkable spatial efficiency.

These designs are based on a special lift system and advanced computation; and can be a good example for the contribution of the mechanical technologies to the spatial qualities/ design conception in architecture. In order to design such spaces, the designers should have a brief knowledge about the capabilities of such systems and work with and cross-disciplinary team.

Figure 3. Swisstech Convention Centre- EPFL (URL-2, 2021)

The other important building parts using mechanical components are the façade and envelope systems. Different from many adaptive façade systems, which only respond to the environmental conditions, some innovative envelope systems, which define the main architectural/ functional characteristics of the buildings, have been emerged for a few decades. "The Shed", designed by DS+R (Figure 4), and "Sliding House", designed by drMM (Akgün, 2012), are good examples for those building envelopes. In these examples, sliding building parts are not only surfaces protecting buildings from external environmental conditions; on the contrary, they are the most important elements that constitute the main architectural character of the building. As an example, at Sliding House, the sliding wooden roof moves along rails set into the ground and creates shifting outdoor living areas between the detached building parts as well as altering views, lighting conditions and the sense of enclosure inside the house. Similarly, the huge steel envelope of the Shed creates an enclosed multipurpose space that can serve an infinite variety of uses, when it is deployed. When the envelope shell is nested over the base building, a 1800m^2 open space is obtained for outdoor programming (URL-3, 2021).

Figure 4. Transformable Roof of "the Shed" (URL-3, 2021)

3.3. Adaptability in Building Envelopes

Concept of adaptability is very common in the design of building envelopes. This is because; envelope is the only physical interface of a building with the physical environment and the urban context. Thus, the building envelope is not only the group of surfaces separating the building from the exterior climatic conditions, but also the interface to interact with the society. For a few decades, the interaction of the façades and roofs with the environmental conditions and the users has gained importance.

Adaptability in building envelopes can be realized in two groups: Climate-adaptive building shells and performative skins. Deployable, retractable, foldable roofs/ shading devices and adaptive glass/ glazing technologies are mostly in the first group. Because of their great efficiency against the environmental conditions such as wind, rain and sun, adaptive shading systems and foldable systems are so popular climate-adaptive building systems in architecture. In other words, the vast majority of the adaptive envelope systems are somehow related to climatic control.

Retractable roof of Wimbledon Centre Court (Figure 5) designed by SCX Special Projects, deployable shading devices of Al Bahr Tower designed by Aedas, diaphragm-like façade panels of Arab World Institute designed by Jean Nouvel, foldable shading devices of ThyssenKrupp Headquarters designed by JSWD and Kiefer Technic Showroom designed by Ernst Giselbrecht are good examples of this group of adaptive façade/ roof systems.

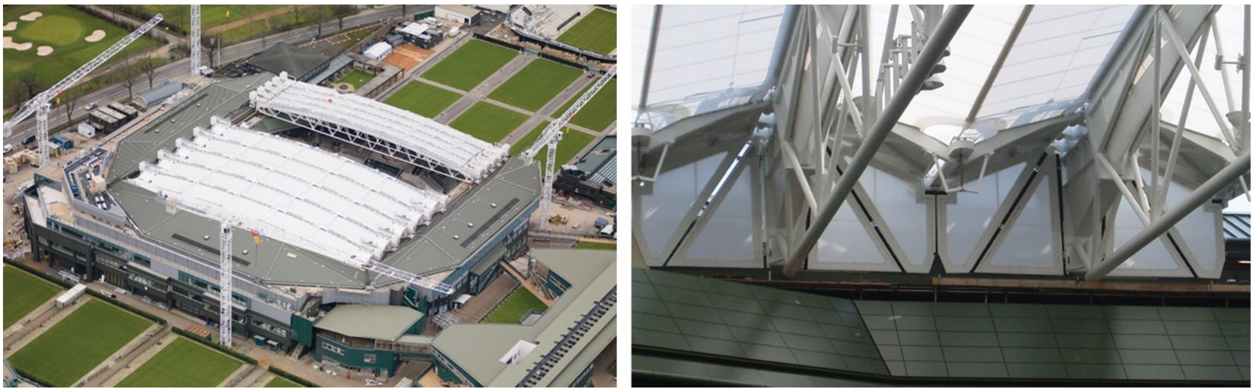

Figure 5. Retractable Roof of Wimbledon Centre Court (URL-4, 2021)

The second group of adaptive façade systems are the performative skins. Interactive façades/ shells and media walls/ façades, which create interactivity between the building and the user/ society can be expressed in this group (Biloria & Sumini, 2009). These systems mostly do not have any climatic/ environmental aims, or these aims are not the primary design objective. Instead, movable/ interactive features of these buildings play a part in the architectural aesthetic, as the interplay of image and technology.

Façade of the "One Ocean, Thematic Pavilion EXPO 2012" by SOMA, "The FLARE Interactive Façade" and interactive media façade of Iluma Shopping Mall are the well-known examples of interactive/ performative façade systems.

While all other examples except Iluma create the interactivity through the movement of the façade panels/ surfaces synchronously, Iluma uses light.

The movable façade of the Bund Finance Centre (designed by Foster and Partners and Heatherwick Studio) is another innovative example for interactive building skins. This façade consists of a veil system with three layers, which adapts to the changing use of the building and reveals the stage on the balcony and views towards Pudong (URL-5, 2021).

Figure 6. Bund Finance Centre (URL-5, 2021)

4. Future Perspectives

For a few decades, use of the adaptive systems in architecture and structural engineering has increased dramatically. Fully computer-controlled responsive structures/ façades/ shading devices, transformable building components with fully automation, responsive building materials made up of smart materials, interactive façade/ wall systems are not extreme or surprising any more. Due to the rapid development of computer technologies, design computing, automation and material science, the demand for such systems will continue rising. If structural and technical advancements drive this trend and demand, we could be approaching a specific turning point in architecture, where technology is directing architectural aesthetics. At this point, two questions may be asked: How can these systems affect or change architecture in the future? Are the architects, engineers and the education systems ready for this change? This section tries to answer these questions.

4.1. Potential Applications

Parallel to the development in the automation, computation, material and design technologies, the buildings and their structural systems are getting more advanced and new types of systems appear every day. New approaches to architecture/ structural design have been evolved and new materials have been invented to fulfil human needs more accurately and thoroughly, ranging from traditional structures to adaptive structures, sensory structures to controlled structures, active structures to intelligent structures (Lan, 2004).

As an example, to this dramatic change in technology of structures; active structural control methods were just a hypothetical approach a few decades ago, but thanks to the sensor and control technologies, the structures of today can respond to the dynamic loads in a few seconds.

At this point, it is possible to ask: What is next? In next fifty years, it will not be a surprise to see the robotic structures or structural mechanisms, which allow huge simultaneous transformations in a few seconds. Again, it will not be an unexpected situation to see robotic systems/ robot arms constructing the buildings. The research studies on smart materials reveal new materials every day. For this reason, it would not be wrong to predict that these materials will be much more common in the construction industry and our daily lives in the future.

Responsive technologies are gaining importance gradually, and novel responsive façade/ roof systems have been designed that can interact with the user and environment. These systems will have more interaction and formal/ chemical capabilities in the future.

Globally, sustainability and resource awareness are one of the most important topics of the era. By the help of material technologies and active structural control systems, it will not be wrong to say that the buildings will be lighter than today.

As a summary, it can be claimed that all these new technologies have been developed to make our living environment more comfortable, and help us to adapt to the existing environment. This will continue in the future, as well.

4.2. Change of Design Philosophy

In the early periods, the master builders were responsible for both the design and the construction of the buildings, and dealt with all planning, spatial organization, technical and structural issues. However, a divergence appeared in the Renaissance, and the disciplines of architecture and structural engineering separated as two different professions in the mid of 18th century with the establishment of engineering schools. Although this provides many advantages, it has also created a gap between two professions. The architects started to focus on solely the building design rather than the structural design. Likewise, the structural engineers paid inadequate attention to the architectural spaces.

Nowadays, the gap between architecture and engineering has begun to be questioned again. Not only the advanced buildings, even the average buildings of today have many automated systems/ materials; and relationships between different disciplines have gained importance for design and integration of these advanced systems to the buildings and structures.

The cross-disciplinary approach is more crucial for the design of adaptive structures. This is because; this research/ design area has always been at the intersection point of architecture, structural engineering and mechanism design. Material science and mechatronics have already joined this intersection for a few decades (Figure 7). The designers of adaptive systems should be aware of the state of art in all these disciplines and should deal with the design problem in a cross-disciplinary manner. This means, the design philosophy of today should be updated according to the needs of the era.

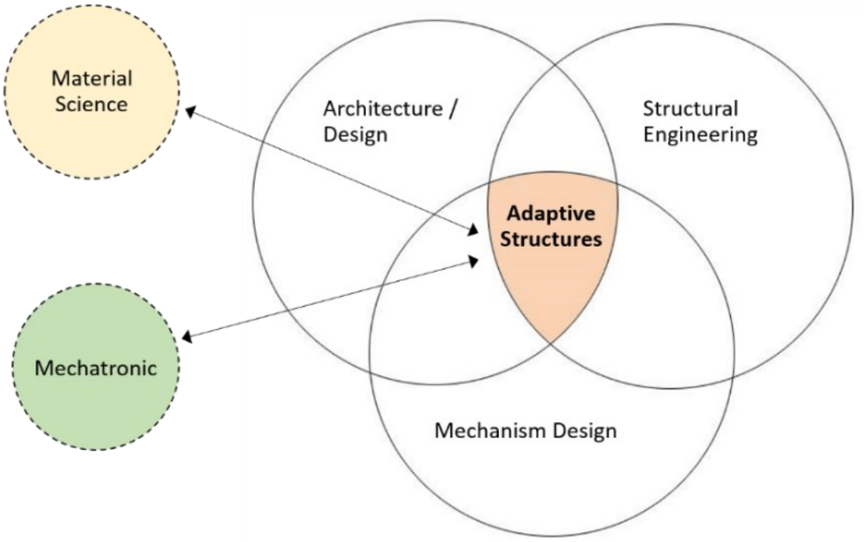

Figure 7. Cross-disciplinary Character of Adaptive Systems (Developed by the Author)

Today, thanks to the user-friendly software packages, automation systems and computation of robotic technologies are easier to learn. Expertise for many complex systems are already uploaded on the internet and can be seen as videos. All these make the process easier for the ones, who are interested in expertise of the topic.

However, the majority of our professional education system still ignores these contemporary tools and design approaches. Maybe even the education systems and curricula of such disciplines should be updated according to the needs of the digital era. Otherwise, many of the engineers and architects of the future will not be able to meet the requirements of the era.

5. Conclusions

Throughout history, architects and structural engineers have always searched for new materials and design methods to create adaptive buildings, building parts and structures that can adapt to ever-changing environmental, spatial and functional requirements. Parallel to the rapid development of computer, automation and material technologies, this trend has increased dramatically for a few decades. This paper introduces contemporary adaptive systems in architecture and structural engineering; and presents a future perspective for these systems and their potential applications in the construction industry.

Particularly, the paper begins with the summary of different methods to design/ control/ actuate adaptive systems and structures. Some of these approaches rely on the incorporation of actuators into conventional structures others necessitate the design of the entire structure/system based on the form and movement of the actuation; and still others necessitate the use of special materials. Secondly, contemporary examples using these methods has been introduced systematically. Finally, future perspectives of the author for the adaptive systems have been explained.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of Interests

The authors declare no conflict of interest.

References

Addington, d. M., & L.shock, D. (2005). Smart Materials and New Technologies For the architecture and design professions. *Elsevier*.

Akgün, Y. (2012). Biçim Değiştirebilen Yapılar ve Mimariye Kattıkları. *Ege Mimarlık*, *1*(80), 42–45. Retrieved from http://egemimarlik.org/sayi-80/index.php

Arena, G., M. J. Groh, R., Brinkmeyer, A., Theunissen, R., M. Weaver, P., & Pirrera, A. (2017). Adaptive compliant structures for flow regulation. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *473*(2204), 20170334. https://doi.org/10.1098/rspa.2017.0334

Biloria, N., & Sumini, V. (2009). Performative Building Skin Systems: A Morphogenomic Approach towards Developing Real-Time Adaptive Building Skin Systems. *International Journal of Architectural Computing*. https://doi.org/10.1260/1478-0771.7.4.643

Bossens, F., & Preumont, A. (2001). Active tendon control of cable-stayed bridges: a large-scale demonstration. *Earthquake Engineering & Structural Dynamics*, *30*(7), 961–979. https://doi.org/https://doi.org/10.1002/eqe.40

Culshaw, B. (1992). Smart Structures—a Concept or a Reality? *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, *206*(1), 1–8. https://doi.org/10.1243/PIME_PROC_1992_206_302_02

Fateh, A., & Hejazi, F. (2021). Development of analytical model of nonlinear stiffness bracing system for structures subjected to dynamic load. *Asian Journal of Civil Engineering*, *22*(4), 789–805. https://doi.org/10.1007/s42107-021-00347-2

Gantes, C. J. (2001). *Deployable structures : analysis and design*. Southampton: WIT Press.

Garrido, H., Curadelli, O., & Ambrosini, D. (2014). Semi-active friction tendons for vibration control of space structures. *Journal of Sound and Vibration*, *333*(22), 5657–5679. https://doi.org/https://doi.org/10.1016/j.jsv.2014.06.018

Golafshani, A. A., Rahani, E. K., & Tabeshpour, M. R. (2006). A new high performance semi-active bracing system. *Engineering Structures*. https://doi.org/10.1016/j.engstruct.2006.03.032

Guo, T., Lu, Q., & Li, J. (2008). PI force feedback control for large flexible structure vibration with active tendons. *Acta Mechanica Sinica/Lixue Xuebao*. https://doi.org/10.1007/s10409-008-0203-9

Jann-Nan, Y., & Fanis, G. (1979). Active Control and Stability of Cable-Stayed Bridge. *Journal of the Engineering Mechanics Division*, *105*(4), 677–694. https://doi.org/10.1061/JMCEA3.0002513

Johnson, A., Zheng, S., Nakano, A., Schierle, G., & Choi, J. H. (2019). Adaptive kinetic architecture and collective behavior: A Dynamic analysis for emergency evacuation. *Buildings*. https://doi.org/10.3390/buildings9020044

Korkmaz, K. (2004). *An Analytical Study of the Design Potentials in Kinetic Architecture*. Izmir Institute of Technology.

Kronenburg, R. (2007). *Flexible : architecture that responds to change*. London: Laurence King Publishing.

Lan, Y. (2004). Adaptive structures and architectures for the future. *Proceedings of the Institution of Civil Engineers*, *157*(2), 129–136. https://doi.org/https://doi.org/10.1680/stbu.2004.157.2.129

Lewis, C., & King, M. (2014). Designing the world's largest dome: the National Stadium roof of Singapore Sports Hub. *The IES Journal Part A: Civil & Structural Engineering*, *7*(3), 127–150. https://doi.org/10.1080/19373260.2014.911485

Lienhard, J., Schleicher, S., Poppinga, S., Masselter, T., Milwich, M., Speck, T., & Knippers, J. (2011). Flectofin: A hingeless flapping mechanism inspired by nature. *Bioinspiration and Biomimetics*. https://doi.org/10.1088/1748-3182/6/4/045001

Loh, C.-H., Lin, P.-Y., & Chung, N.-H. (1999). Experimental verification of building control using active bracing system. *Earthquake Engineering & Structural Dynamics*, *28*(10), 1099–1119. https://doi.org/https://doi.org/10.1002/(SICI)1096-9845(199910)28:10<1099::AID-EQE857>3.0.CO;2-#

Mekhzoum, M. E. M., Qaiss, A. el kacem, & Bouhfid, R. (2020). 1 - Introduction: different types of smart materials and their practical applications. In R. Bouhfid, A. el K. Qaiss, & M. B. T.-P. N.-B. S. M. Jawaid (Eds.), *Woodhead Publishing Series in Composites Science and Engineering* (pp. 1–19). https://doi.org/https://doi.org/10.1016/B978-0-08-103013-4.00001-7

Neuhaeuser, S., Weickgenannt, M., Witte, C., Haase, W., Sawodny, O., & Sobek, W. (2013). Stuttgart smartshell - A full scale prototype of an adaptive shell structure. *Journal of the International Association for Shell and Spatial Structures*.

Neuhäuser, S. (2014). *Untersuchungen zur Homogenisierung von Spannungsfeldern bei adaptiven Schalentragwerken mittels Auflagerverschiebung*.

Özgen, G., & Erdinç, U. (2017). Lecture Notes for ME 493 Introduction to Smart Structures and Materials. Retrieved April 18, 2021, from http://courses.me.metu.edu.tr/courses/me493/

Pellegrino, S. (2002). *Deployable structures* (Vol. 412). Springer Science & Business Media.

Preumont, A., Achkire, Y., & Bossens, F. (2000). Active Tendon Control of Large Trusses. *AIAA Journal*, *38*(3), 493–498. https://doi.org/10.2514/2.987

Schnädelbach, H. (2010). Adaptive Architecture - A Conceptual Framework. *Proceedings of MediaCity: Interaction of Architecture, Media and Social Phenomena, Weimar, Germany*, 523–555.

Schumacher, M., Vogt, M.-M., & Krumme, L. A. C. (2019). *New MOVE*. https://doi.org/doi:10.1515/9783035613629

Senatore, G., Duffour, P., & Winslow, P. (2018a). Energy and Cost Assessment of Adaptive Structures: Case Studies. *Journal of Structural Engineering*. https://doi.org/10.1061/(asce)st.1943-541x.0002075

Senatore, G., Duffour, P., & Winslow, P. (2018b). Exploring the application domain of adaptive structures. *Engineering Structures*. https://doi.org/10.1016/j.engstruct.2018.03.057

Sobek, W., Bergmann, C., & Haase, W. (2012). Hafif Yapı Elemanları Tasarımı: Stuttgart Üniversitesi Hafif Strüktürler ve Kavramsal Tasarım Enstitüsü'nün Güncel Çalışmaları. *Ege Mimarlık*, *3*, 8–13. Retrieved from http://egemimarlik.org/82/8.pdf

Soong, T. T. (1988). State-of-the-art review. Active structural control in civil engineering. *Engineering Structures*. https://doi.org/10.1016/0141-0296(88)90033-8

Soong, T. T., & Chang, J. C. H. (1982). Active Vibration Control of Large Flexible Structures. *Shock and Vibration Bulletin*.

Soong, T. T., Reinhorn, A. M., Aizawa, S., & Higashino, M. (1994). Recent structural applications of active control technology. *Journal of Structural Control*, *1*(1-2), 1–21. https://doi.org/https://doi.org/10.1002/stc.4300010101

Tzonis, A., & Lefaivre, L. (1995). *Movement, structure and the work of Santiago Calatrava*. Basel; Boston: Birkhäuser.

URL-1. (2017). Refined Scissoring: Flexible Bridge in Geneva. Retrieved April 20, 2021, from Detail Online Magazine website: https://www.detail-online.com/blog-article/refined-scissoring-flexible-bridge-in-geneva-29614/

URL-2. (2021). Gala Systems. Retrieved April 23, 2021, from https://www.galasystems.com/en/projects/

URL-3. (2021). Diller Scofidio and Renfro Architects. Retrieved April 23, 2021, from https://dsrny.com/project/the-shed

URL-4. (2021). Wimbledon Centre Court Retractable Roof. Retrieved April 23, 2021, from https://www.scx.co.uk/case-studies/wimbledon-centre-court-retractable-roof/

URL-5. (2021). Bund Finance Centre. Retrieved April 23, 2021, from https://www.archdaily.com/881511/bund-finance-centre-foster-plus-partners-plus-heatherwick-studio?ad_medium=gallery

Wada, B. K. (1990). Adaptive structures - An overview. *Journal of Spacecraft and Rockets*, *27*(3), 330–337. https://doi.org/10.2514/3.26144

Zuk, W., & Clark, R. H. (1970). *Kinetic architecture*. New York: Van Nostrand Reinhold.