AN INVESTIGATION ON THE PERFORMANCE OF ALUMINIUM PANEL CURTAIN WALL SYSTEM IN RELATION TO THE FACADE TESTS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

BANU NUR ŞENGÜN DOĞAN

IN PARTIAL FULLFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
BUILDING SCIENCE IN ARCHITECTURE

JANUARY, 2013

Approval of the thesis:

AN INVESTIGATION ON THE PERFORMANCE OF ALUMINIUM PANEL CURTAIN WALL SYSTEM IN RELATION TO THE FACADE TESTS

submitted by **BANU NUR ŞENGÜN DOĞAN in** partial fulfillment of the requirements for the degree of **Master of Science in Building Science in Architecture Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen ______________________
Dean, Gradute School of **Natural and Applied Sciences**

Assoc.Prof. Dr. Güven Arif Sargın ______________________
Head of Department, **Architecture**

Inst. Dr. Berrin Zeytun Çakmaklı ______________________
Supervisor, **Architecture Dept., METU**

Examining Committee Members:

Assoc. Prof. Dr. Ayşe Tavukçuoğlu ______________________
Architecture Dept., METU

Inst. Dr. Berrin Zeytun Çakmaklı ______________________
Architecture Dept., METU

Assoc. Prof. Dr. Soofia Tahira Elias Özkan ______________________
Architecture Dept., METU

Assoc. Prof. Dr. M.Halis Günel ______________________
Architecture Dept., METU

H.Emre Ilgın, M.Sc. ______________________
Architect, Ministry of Health

Date: ______________________

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name: Banu Nur Şengün Doğan

Signature:

ABSTRACT

AN INVESTIGATION ON THE PERFORMANCE OF ALUMINIUM PANEL CURTAIN WALL SYSTEM IN RELATION TO THE FACADE TESTS

Şengün Doğan, Banu Nur
M.Sc., in Building Science, Department of Architecture
Supervisor : Inst. Dr. Berrin Zeytun Çakmaklı

January, 2013, 96 pages

Extruded aluminium has become the material of choice for building envelope owing to its lightness, wide range of possibilities for profile design, durability and the eco-friendly attitude. In the light of recent technological developments in metal and glass industries, there has been various new approaches towards aluminum curtain wall systems which are mostly preferred by architects in high-rise buildings. Herein, the panel curtain wall system is determined as innovative and the modern aluminium curtain wall system. Furthermore, in the recent prestigious high-rise buildings, the demand of the architects and the contractors begins to replace the conventional curtain wall system which is constructed via stick construction technique, with panel curtain wall system which is applied to the building in a modular form . The main aim of this study is to investigate why the panel curtain wall system comes to the forefront especially for high-rise buildings. Accordingly, the basic architectural, structural and constructional design principles of unitized aluminium curtain wall systems are defined, analyzed and then the advantages and disadvantages of this system are pointed out from an architectural point of view.

In order to evaluate the performance of panel curtain wall system against environmental factors, the facade tests, which are new and still-developing methods in Turkey, are used. The extensive facade tests have been conducted on full-scale specimen under field conditions reproduced in an equipped test chamber by authorized facade testing company and the assessment of this curtain wall performance was provided accordance with related standards. The two story full-size specimen, was 3000 mm to 7600 mm, belongs to one of the prestigious office towers constructed in İstanbul. The facade tests conducted to the specimen include watertightness, air permeability, wind resistance and building movement tests.

In this study, the performance criteria of panel curtain wall system were investigated not only against environmental factors but also against human sourced factors. It is expected that this study will provide a guideline for system designers on the future research and development phase and for architects on the selection of curtain wall systems for their buildings due to the conducted test results and other advantages taken throughout this study.

Keywords: Panel (Unitized) Curtain Wall System, Facade Tests, Performance Criteria, Aluminium Curtain Walls, High-rise Buildings

ÖZ

ALÜMİNYUM PANEL GİYDİRME CEPHE SİSTEMİNİN CEPHE TESTLERİNE GÖRE PERFORMANSININ ARAŞTIRILMASI

Şengün Doğan, Banu Nur
Yüksek Lisans, Yapı Bilgisi Anabilim Dalı, Mimarlık Bölümü
Tez Yöneticisi : Dr. Berrin Zeytun Çakmaklı

Ocak, 2013, 96 sayfa

Ekstürize edilmiş alüminyum, hafif oluşu, taşıyıcı tasarımında tanımış olduğu geniş olanaklar, dayanıklılığı ve çevre dostu yaklaşımıyla bina kabuğu tasarımında vazgeçilmez bir malzeme olmuştur. Metal ve cam endüstrisinde en son gelinen teknolojik gelişmeler ışığında, mimarlar tarafından çoğunlukla yüksek binalarda tercih edilen alüminyum giydirme cephe sistemlerinde yeni yaklaşımlar ortaya çıkmaktadır. Bu noktada, panel cephe sistemi yenilikçi ve modern sistem olarak tanımlanmaktadır. Bununla birlikte, son yapılan prestijli yüksek bina projelerine bakacak olursak, mimarların ve yatırımcıların talebinin çubuk yapım tekniğiyle uygulanan geleneksel cephe sistemlerinden modüler olarak uygulanan panel cephe sistemlerine yöneldiğini söyleyebiliriz. Bu çalışmanın ana amacı, panel cephe sistemlerinin özellikle yüksek binalarda neden ön plana çıktığını araştırmaktır. Bu doğrultuda panel cephe sistemlerinin mimari, taşıyıcı ve yapısal tasarım prensipleri belirlenip analiz edilerek, mimari bakış açısıyla avantajları ve dezavantajları ortaya konmuştur.

Panel cephe sistemlerinin çevresel etmenlere karşı performansını değerlendirmek için, ülkemizde yeni ve her geçen gün gelişmekte olan cephe testi metodu kullanılmıştır. Gerçek arazi şartlarının yansıtıldığı donanımlı test odasında gerçek boyutlarda tasarlanan test numunesi üzerinde kapsamlı cephe testleri yetkili cephe testi firması tarafından uygulanmış ve performans değerlendirmesi ilgili standartlara göre yapılmıştır. İki kat ölçeğinde 3000 mm genişlik ve 7600 mm yüksekliğindeki test numunesi, İstanbul'da yapılmakta olan prestijli bir ofis kulesine aittir. Uygulanan cephe testleri su sızdırmazlık, hava geçirgenliği, rüzgar direnci ve bina hareketi testlerini içermektedir.

Bu çalışmada panel cephe sisteminin sadece çevresel faktörlere göre değil, insan kaynaklı faktörlere göre göstermiş olduğu performans kriterleri de araştırılmıştır. Bu çalışmanın, uygulanan cephe testlerinin sonuçları ve çalışma süresince elde edilen avantajlar doğrultusunda, sistem üreticileri için araştırma ve geliştirme safhasında, mimarlar için ise binalarda uygulayacakları cephe sistemlerinin seçimi açısından yol gösterici olması beklenmektedir.

Anahtar Kelimeler: Panel Cephe Sistemi, Cephe Testleri, Performans Kriterleri, Alüminyum Giydirme Cepheler, Yüksek Katlı Binalar

To My Mother Derya Şengün, My Father Recai Şengün
My Sisters Bengü,Gökçe,Göksu Şengün
and
My endless love Ömer Faruk Doğan

ACKNOWLEDGEMENTS

I owe my deepest gratitude to my supervisor Inst. Dr. Berrin Zeytun Çakmaklı. I would like to thank for her kind approach and persistent guidance and patience throughout the study. This work would not have been possible without her support. I would also like to thank my jury members for their valuable suggestions and comments in the development of this study.

I would like to express my sincere thanks and appreciation to Murat Seyhan who is the general manager of the Facade Testing Instititute, and also special thanks to other staffs of the same company Öner Arslan and Oktay Usta for their help and generous support.

I am also grateful to Prof. Dr. Abdurrahman Kılıç and Eray Kaya for providing me the documents I needed.

Special thanks to my husband Ömer Faruk Doğan for his immeasurable assistance and unshakeable faith in me. Beginning from the first draft of the study, he has always helped and suggested me in every phase of the study.

I am very grateful to my cousins Özge and Tolga Moğulkoç for their support and assistance.

Lastly, I would like to express my sincere appreciation and gratitude to my parents Derya Şengün and Recai Şengün, my sisters Bengü, Gökçe, Göksu Şengün for their continuous encouragement and love.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

ABBREVIATIONS

AAMA	American Architectural Manufacturers Association
DSF	Double Skin Façade
EN	European Standard
h	Hour
Hz	Hertz
L	Liter
Low-E	Low Emissivity
m	Meter
min	Minute
TS	Turkish Standard

CHAPTER 1

INTRODUCTION

In this chapter, at argument part, the background information, framework and the underlying concern of the study is explained and the scope of the study is mentioned. The ideas and concepts with regards to architectural and constructional perspective are argued. In the next part, the aim and the objectives of the study are given. In the following part the procedure of the study is explained and finally under disposition part the contents of the study are introduced.

1.1 Argument

With the increase number of high-rise buildings, there have been significant improvements in curtain wall design, which is inextricably linked to developments in technology, innovations in design and construction techniques. Accordingly, the metal and glass combinations have appeared in a fully engineered system as a building envelope. Within this framework, the recent approach in curtain wall design is providing a connection between the exterior of the building to the interior space with minimum visual barriers and consequently, the building envelope takes more light in and becomes more translucent and transparent part in architectural composition, which provides a chance for architects to design lighter and aesthetic curtain wall systems. Another reason for the high rise building facades to be so much transparent is to respond to the needs of working/living people in these buildings to interact with nature and living surroundings, in other words physiological and psychological needs. As every living being, the need of a human, to be aware of the current medium, to sense day or night, rain or snow in other words "the need to sense time" should not be ignored. This is the best way to correspond the necessities of people via the combinations of glass and metal components in building facade. Herein, extruded aluminium has also a significant role for the buildings to be lighter and more transparent which constitute easily formed and thin cross sectioned structural members. In addition, this material is preferred in building construction due it provides facilities in terms of flexibility in design, constructional aspect, maintenance factor and the sustainable approach. That's why not only tall-super tall buildings but also a low rise office, commercial or residential buildings has been covered by means of aluminium curtain wall systems instead of stone, wood or other traditional materials in contemporary architecture.

From the point of architectural perspective, aluminium curtain wall systems have brought out a new architectural approach affecting not only facade design but also the perception of architecture. Especially, in high-rise buildings, the building envelope with the reflective effect of glasses gives a uniform impression on people in terms of power and modernity by means of its homogenous and gigantic appearance. Moreover, with regards to urban aspect, the tall-buildings with their fascinating facades have a great impact on city silhouette. Consequently, the facade is not only a simple barrier providing a protection against environmental factors but also it has a responsibility to the surrounding urban fabric.

There have been a growing interest and more performance expectations from aluminum curtain wall systems. Previously, the main performance criteria were limited to effective light, water and heat control whereas with the new technological developments, they are required to be cost-efficient with the minimum duration for montage, high-performance in seismic and wind control for the buildings. This fact enables the system designers of the curtain wall system to design more advanced and durable aluminium sections applied for building envelopes. Moreover, increase the demand of lighter, aesthetic, flexible and eco-friendly materials, faster construction techniques and cost-efficient applications speed up the improvements in aluminium curtain wall systems.

But unfortunately, literature survey indicates that there are limited academic publications and books about aluminium curtain wall systems. The number of researches is inadequate in Turkish printed publications. About this subject, the information can be getting from people who have sector experience or can be getting from the aluminium system manufacturers. In addition, the theses which are written about this subject are similar to each other and the context of these researches is mostly about general information and the classification or the performance of aluminium curtain wall systems. In these theses, the authors have focused on the most known curtain wall systems. But the modern type of curtain wall system, the new assemblage techniques and recent glazing types are not mentioned adequately.

Stick (frame) construction is the initial and widely-used a construction technique of aluminium curtain wall system. Conventional and structural glazing curtain wall systems are well-known and preferable systems constructed with stick construction technique. But there have been some problems observed related with the stick construction technique. It is known that the systems, which are constructed with this technique, may have in difficulties while tolerating horizontal loads because the aluminium frames are fixed to the building in this construction technique. In addition, the erection period of aluminium frames, glazing part and the other components takes long time; in other words there are maximum site labor and minimum factory labor. Moreover, in this technique, there is a need of using scaffold for installation, which may cause problems in construction period especially at high-rise buildings. Due the members of the aluminium frames are fixed to the building in the construction phase, the maintenance of the system components may be difficult in this technique and the maintenance of the system components should be implemented at construction site. So that in order to minimize these problems, the aluminium system designers have been working on the new systems and construction techniques. Accordingly, panel construction technique is the recent technique, which gives its name to the panel system. In the recent years, with respect to prestigious projects unitized (panel) curtain wall system, which is called modern and innovative, is becoming more preferred as building envelope especially for tall buildings. The reasons why the panel curtain wall system comes to the forefront especially for high-rise buildings is the goal of this investigation and it is intended to analyze how this system behaves against these problems mentioned above. As distinct from other aluminium curtain wall systems, in panel curtain wall system, the aluminium sections and translucent (glass) components are combined together in a factory then they are carried to the construction site and erected to the facade. It means that this system is carried and applied as modular form. The systems designers and the architects indicate that the modular form provides significant advantages for curtain wall design, which will be searched and handled throughout this study.

It is critical to control environmental and human sourced factors for the performance of curtain wall systems. Accordingly, the curtain wall system, act as a selective, permeable membrane and protective coat between the environment and the building, are directly exposed to environmental factors. These environmental factors consist of air, heat, water, moisture, fire, sound, wind, and seismic movements. Furthermore, human-sourced factors, which are based on the quality of workmanship and assemblage on the construction site, are directly affect the durability and the performance of the system. Within this framework, it is significant to point out the methods for measuring the performance of the curtain wall systems. Herein, facade tests are new approaches for evaluating the success of the curtain walls against the environmental conditions. These tests are conducted on the specified mock-up in a factory by authorized companies. Moreover, the facade tests can be applied for the research and the development stage of the aluminium systems or can be used to assess the success of the curtain wall system for specific projects. So that it is necessary to analyze the methods, types and the application details of these facade performance tests.

As it is mentioned above, there are various aluminium curtain wall systems in terms of building envelopes. But nowadays, the unitized curtain wall system comes to the forefront especially for high-rise buildings. To understand and analyze this modern system, the facade curtain wall tests are preferable methods. It is expected that this research will be a guide for understanding and evaluation of the performance of panel curtain wall system by means of facade tests.

1.2 Aim and Objectives

The recent curtain wall applications in building construction sector show that the unitized (panel) curtain wall system, which is also called the innovative and modern curtain wall system, becomes more preferable from architects and system manufacturers especially for high-rise buildings. The main aim of this investigation is to define, analyze and outline the basic architectural, structural and constructional design principles of unitized aluminium curtain wall systems and point out the advantages and disadvantages of this system in terms of architectural and constructional perspective.

The objective of the study is to determine and examine the performance criteria of aluminium curtain wall systems especially for unitized curtain wall system in terms of environmental and human sourced factors. In order to measure the performance of the building envelope, facade tests, which are new approaches to evaluate the success of the curtain walls, are handled and evaluated in terms of their application details and types throughout this study. In this investigation, the performance of the panel curtain wall system is evaluated by means of conducting specified facade tests by authorized company.

The last objective of this study is to point out the classification and analysis of the curtain wall systems in the light of recent developments. Furthermore, the glazing types, which are mostly used in curtain wall systems, are handled in order to evaluate what the effects of recent improvements in the glazing industry on the curtain wall system are.

1.3 Procedure

The first stage of this study includes the literature survey chapter. It is based on the articles, journals, books and other publications related with this subject. The survey consists of background information and the definitions about the issue, relevant standards and similar studies conducted on this subject. Accordingly, the theses and publications found in the Council of Higher Education library and Middle East Technical University library are examined. During the study, web sites related to this subject are visited. The pioneer aluminium manufacture and glazing companies are searched and the authorized people of these companies are contacted for gathering the catalogues, booklets, technical drawings and related photos.

For the second stage of this study, in order to analyze the performance of the panel curtain wall system via facade tests, one of the pioneer facade testing company in Turkey was determined. It is significant to cooperate with the company not only for technical but also for financial support. Through the personal interviews with the general director of the facade testing company, Murat Seyhan, the permission for attaining the specified panel curtain wall test was taken. Accordingly, at the appointed date and time, the watertightness, air permeability, wind resistance and building movement tests were implemented to the mock-up of the panel curtain wall system which belongs to one of the prestigious towers constructed in İstanbul. Throughout the curtain wall tests, the test engineer Öner Arslan has introduced the test process and the details.

The next stage of this study presents the results of conducting watertightness, air permeability, wind resistance and building movement tests. The graphs and the performance tables were analyzed and related photos taken from the test process were given. In addition, the facade performance tests are criticized and the suggestions on the improvements of the facade tests are mentioned. Furthermore, benefits of panel construction technique in comparison to stick construction technique are handled. Finally, the last stage consists of the overall evaluation and the conclusions of this study.

1.4 Disposition

Including this introduction, the study consists of five chapters. The second chapter introduces the literature survey on the subject domain. In this chapter, the background information and definitions of aluminium curtain wall systems were given. Then, the classifications of aluminium curtain wall systems according to construction technique and design method were handled. Furthermore, the most common glazing types and the combinations used in facade systems were explained. Thereafter, the performance criteria of curtain wall systems were examined in terms of environmental and human sourced factors. In the last subject of this chapter, the brief information about the curtain wall tests implemented to the aluminium facades were given.

In Chapter 3, the survey material and the method were explained. The material of this study, which were mock-up of a panel curtain wall system and the performance curtain wall tests, is presented. Thereafter, the preliminary processes for curtain wall tests were explained and the applied curtain wall tests were pointed out.

The Chapter 4 consists of the results of the conducted performance tests on the panel curtain wall system. Accordingly, the performance tables and the related graphs were evaluated and discussed. In addition, the facade performance tests were criticized and the suggestions on the improvements of the facade tests were stated. Furthermore, benefits of panel construction technique in comparison to stick construction technique were pointed out. Finally, in the last chapter, the concluding remarks of the survey were introduced.

CHAPTER 2

LITERATURE SURVEY

This chapter covers the relevant information in the literature regarding to the subject and methodology of this study. In the first three sections, background information and definitions are given; the classification of aluminium curtain wall systems according to construction technique and design method is defined. The other section is about general properties of different types of glass which are commonly used at aluminium curtain wall systems. Then, the performance criteria that consist of heat, air, water, moisture and fire control, are handled. In the last part, the performance tests conducted on aluminium curtain wall system are given.

2.1 Background Information and Definitions of Aluminium Curtain Wall Systems

The extruded aluminium, which is widely used in curtain wall design as a building material, provides an efficient manufacturing treatment to convert the aluminum into linear sections of complex geometry. The reason why aluminium becomes preferable material in building construction can be explained by evaluating the performance and the properties of aluminium. According to Council for Aluminium in Buildings (CAB), aluminium can easily be pressed and cut, which provides various forms leading up flexible facade design. It is available in numerous shapes and various colors. In addition, the specific weight of the aluminium determined as 2.7 g/cm^3, three times lighter than steel, supplies to work on material in factory site and facilitates transportation to the construction site. Furthermore, aluminium is defined as durable and noncorrosive material, which is a significant factor for the construction of larger facade surface.

In modern architecture within the sustainable framework, the behavior of material against the environment is determinant to become preferable as a construction material. According to this point of view, CAB indicates that aluminium can be recycled again and again without loss of quality, and the remelting of aluminium requires less energy; it saves up nearly 95% of the energy required for primary aluminium production. Furthermore, aluminium is described as a good reflector of visible light as well as heat. Within this framework, the system manufacturers also claim that aluminium claddings provide a great contribution to breathing of a building while comparing other facade materials especially PVC based. The conscious clients and the architects should take into consideration in terms of human health and longevity of the buildings. All these advantages of aluminium mentioned above make aluminium more preferable material especially for the building facade design.

The historical development of using aluminium as building material dates back to 19 th century. Tortu (2006) states that the first aluminium structure is a small square pyramid constructed on the top of Washington Monument in 1884. After two years in 1886, Charles Martin Hall electrolyzed the aluminium so that the aluminium becomes more economic, accessible and available in larger quantities in terms of construction material.

At the beginning of 20th century, the design of the building envelope has been started to undergo a transition from the massive load-bearing wall to the light weight and non-load bearing curtain wall system. The integration of glass as a primary architectural material into curtain wall system leads up new building envelope approach. Since early 20th century, Patterson (2008) mentioned that aluminium has raised to prominence through landmark projects among pioneer architects, such as Walter Gropius, Mies van der Rohe, Peter Behrens etc. In addition, it is stated that the architects focused on transparency, translucency and reflection properties of glass and architecture has been increasingly went towards the manipulation of light, shadow, view and reflection. Considering historical development of building envelope, increasing the strength and durability of glass can be defined as the crucial point leading extensive usage of curtain wall system especially for high-rise buildings. According to Begeç & Savaşır (2004), the tempered or safety glass, which is shattering into small cubes rather than large glass shards, is produced in France in 1928. This fact allows extensive surface glass applications in building construction.

The affects of post-II.World War is mentioned by the same authors as the other significant influence on the process of aluminium curtain wall system. After the Second World War, there has been dramatical demand for new building construction system, which paves the way for prefabrication and mass production technique at almost all building parts to provide rapid construction. So that the curtain wall systems which consists of modular components has become developed. (Begeç & Savaşır, 2004)

After World War II, metal and glass curtain wall systems began to appear on commercial and institutional buildings. Booming post-war economies lead low-cost cladding strategies by maximizing leasable area in a given footprint, which cause an increase in the number of high-rise buildings. In this vein, Güvenli (2006) states that in the early 20th century the discipline of architecture is unexpectedly faced with the responsibility of designing a great number of buildings. The buildings have almost become industrial products influenced from the mass production and standardization. Moreover, the industrial revolution has directed the architecture in terms of transparency and translucency and after Second World War, with the help of development in materials and technology, the aluminium and stainless steel become more preferable as a construction material.

According to Clausen (1991), Equitable Building, which is designed by Pietro Belluschi in 1948 in Portland, has the first aluminium building envelope after the Second World War seen in the figure 2.1. It is mentioned that Belluschi had foreseen the possibility of supplies of aluminum after the war so that he designed the cladding on this basis.

Figure 2.1. Equitable Building, Portland, Oregon, 1948, (Source: L. Calusen, 1991)

Yeomans (2001) stated that the window technology had affected the process of earliest glass curtain wall design. The system developers have improved the aluminium sections and integrated components with respect to the performance criteria of building envelope and market demand. Within this framework, it is mentioned that the initial frame sections helped to understand the developing process of curtain wall design, as indicated in Figure 2.2.

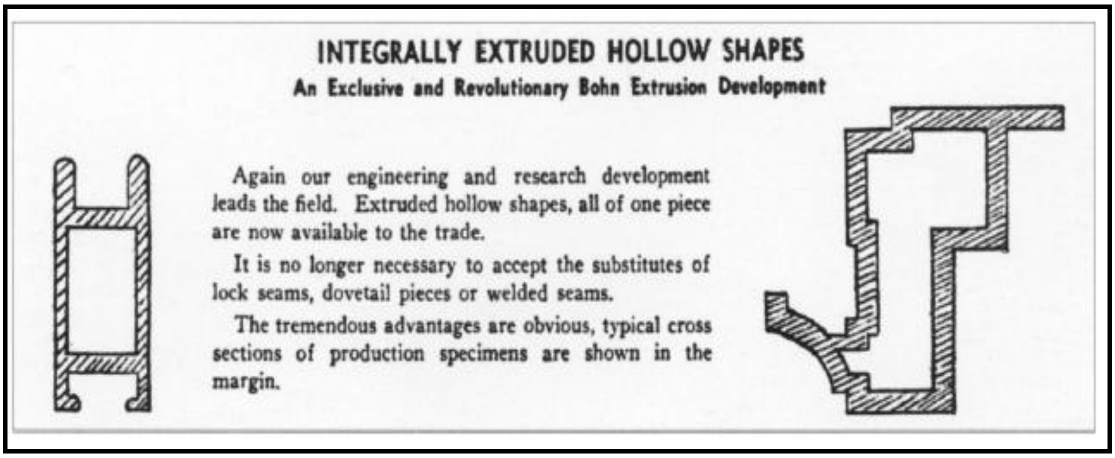


Figure 2.2. Part of An Advertisement of The Bohn Aluminum and Brass Corporation. From Sweet's Catalogue, 1935. (Source: D,Yeomans, 2001)

Begeç and Savaşır (2004) stated that there has been great energy demand so that seeking for sustainable solutions in architectural design was occurred after the energy crisis occurred in 1970. Furthermore, the significant precautions for consuming less energy on the building envelope took into consideration. The envelope becomes not only a barrier between exterior and interior but also it is expected to be sustainable and sensitive to the environment. As a result, aluminium curtain wall system, become a symbol of modernity and level of development and also provides advantages through expected and desired facade design.

The basic definitions of curtain wall system are necessary to evaluate the general concepts and approaches through building facade. Brookes (1998) defined the curtain walls as being non load – bearing walls, usually suspended in front of a structural frame, their own dead and wind loads being transferred to the structural frame through anchorage points. According to Scott (2009) curtain wall is defined as non-load bearing building envelope that typically hangs like a curtain from a structural frame. In addition to these definitions, aluminium curtain wall system can be defined as a type of metal curtain wall which consists of aluminium frames, glazing parts, panels or combinations between them. Sev (2009) stated that curtain wall system is divided into mainly two parts in terms of load : “heavy curtain wall” and “light curtain wall”. And added that heavy curtain walls, which are the generally heavier than 100 kg/m2, consist of precast panels made up from concrete, plastic, stone or metal. The same author continues that light curtain walls are generally not exceeded the 100 kg/m2 so that the aluminium curtain wall system can be categorized under this heading.

2.2 The Classification of Aluminium Curtain Wall Systems According to Construction Technique

The aluminium curtain wall systems are classified in terms of their methods of installation and fabrication. Although the hybrid combinations are possible, most curtain walls are divided into three main categories: stick (frame), semi-panel and panel construction system.

2.2.1 Stick (Frame) Construction Technique

The first construction method that comes to mind due to being a pioneer and widely-used in metal curtain wall systems is frame construction technique. Today, this technique is still common but the improved versions are preferred in building construction. According to Şenkal (2005), the stick (frame) system based on a defined grid system which consist of vertical (mullions) and horizontal (transoms) frame members. The openings between grid systems, framed by aluminium members, are filled with a panel or glass. Patterson (2008) describes in detail, the technique that the vertical and horizontal frame members, which are pre-fabricated and factory painted, are installed and connected together piece by piece at construction site. Glass or other cladding panels are then attached to these members. In addition it is stated that this system is referred to "stick-built" due to its grid based construction method.

Figure 2.3. The Stick (Frame) Construction Technique, (Source: Individual Archive, 2012)

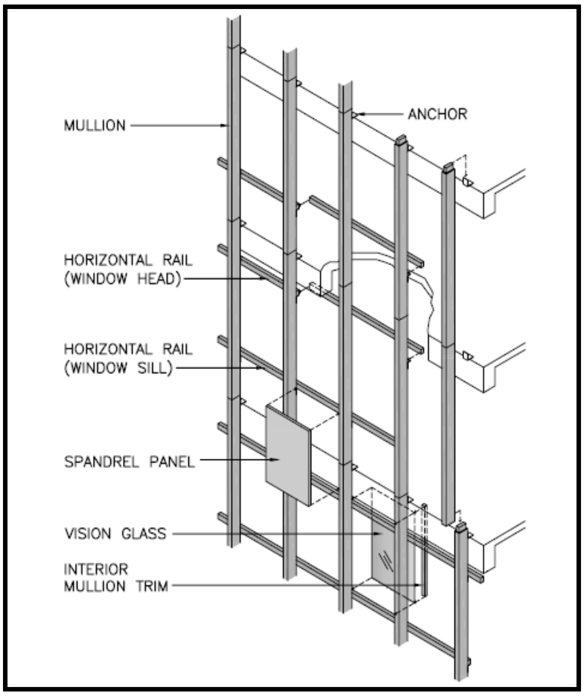


Figure 2.4. Illustration Demonstrates The Characteristics of a Typical Stick (frame) Construction Technique, (Source: Hofmann Architects Journal, Vol:23 ,Issue 1,2006)

Şenkal (2005) explains the installation of stick construction technique. First of all, the assemblage of various sizes and forms of anchorage elements, which are installed to the parapet or each floor area, the anchorage points are determined. Then, the vertical members are installed with the help of anchorage screws from bottom to top. The direction of the system is controlled by anchorage screws providing proper installation. In order to minimize the wind, seismic and thermal movement deflections on the system, the anchorage members should be arranged to allow the movement of vertical and horizontal members. Lastly, the installation is completed by integrating glass or panels into the aluminum grid system.

The advantages and disadvantages of the system are explained by Scott (2009). It is mentioned that most stick systems are standard, off-the-shelf products; thus they have relatively low material cost. Moreover, the facility of an efficient package technique for separate system components provides low expense of shipping and handling. The author continues with the disadvantages of the system. The main disadvantage of the stick construction technique derives from the method of assembly in the site. This mostly involves a slower pace, high labor costs, and greater potential problems concerning the quality and precision of the work. Furthermore, stick systems are usually limited to low or midrise applications. Within this framework, Atalay (2006) states that due to low performance against building movements, this system is inappropriate for large surface applications. In addition to this, the duration of construction increase due to unmodulated construction components comparing with modular construction technique. Moreover, the difficulty of working on high-rise buildings especially in worse weather conditions in winter slowdown the assemblage of curtain wall systems. In this case, scaffolding and other additional catwalks, which are compulsory for construction, should be used cautiously. So that, stick system may be hazardous construction technique for workers in case of bad weather conditions.

2.2.2 Semi-Panel Construction Technique

The semi-panel construction, which can be described as the improved version of the stick (frame) construction technique in terms of details and structural solutions, become pioneers in the development of panel construction technique. According to Doğruel (2010), the members of the semi - panel system, which have a resemblance to a floor-height panel, produced as vertical stripes. In this system, every floor behaves like independent from each other but they provide a unique appearance looking from both exterior and interior. The same author continues that since 15 years in USA as prestigious projects, which are World Trade Center, Sears Tower etc., are constructed with semi panel construction technique. In Turkey, the first application of this system is Sabancı Center in 1991 in İstanbul.

Figure 2.5. The Sabancı Center, İstanbul
(Source: Çuhadaroğlu Aluminium Refereans Brocure, 2011)

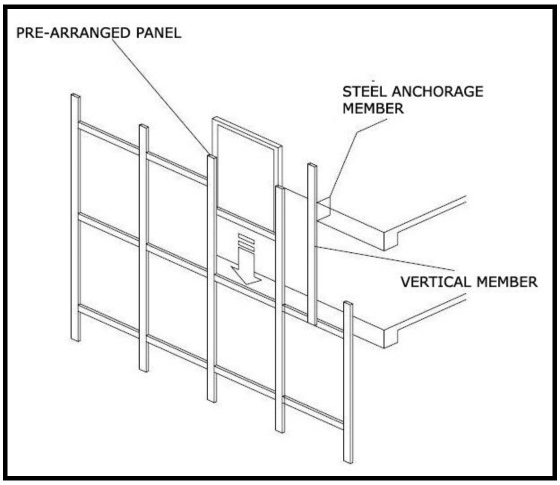


Figure 2.6. Schematic Diagram of Semi-Panel Construction Technique
(Source: Doğruel, 2010)

Şenkal (2005) explained the installation of glazing part. The glass is mounted to the facade at the construction site after anchorage members are installed to the building. Then, the heat and sound insulation materials are applied to the spandrel parts of the building. Also noted by the author is that this system is appropriate and economic towards seismic movements against both horizontal and vertical directions especially for high-rise buildings.

2.2.3 Panel (Unitized) Construction Technique

Panel construction technique, which is the most contemporary method, gives its name to the panel curtain wall system. İş bank complex is the first application of panel construction technique in Turkey. (Şenkal,2005)

Figure 2.7. İş Bank Complex, İstanbul
(Source: Çuhadaroğlu Aluminium Refereans Brocure, 2011)

Atalay (2006) explains that panel curtain wall system is composed of a series of preassembled units which have a story height and one or two axes width. They are assembled and glazed in the factory, and they are carried to the construction site.

According to BCI (Architectural Glazing and Building Enclosures Company), for the typical unitized installation, firstly the anchor points are identified, and a grid line in accordance with the architectural project is specified. Then concrete cast-in-place channel inserted due to the grid line and the curtain wall brackets are positioned over the channels, as indicated in Figure 2.8. Moreover, T-bolts or anchor bolts are inserted into the bracket, and then firmly screwed by tightening bolts. On the other hand in Turkey, at most of the building site, the aluminium companies apply the curtain wall bracket directly on a slab without inserting channel.

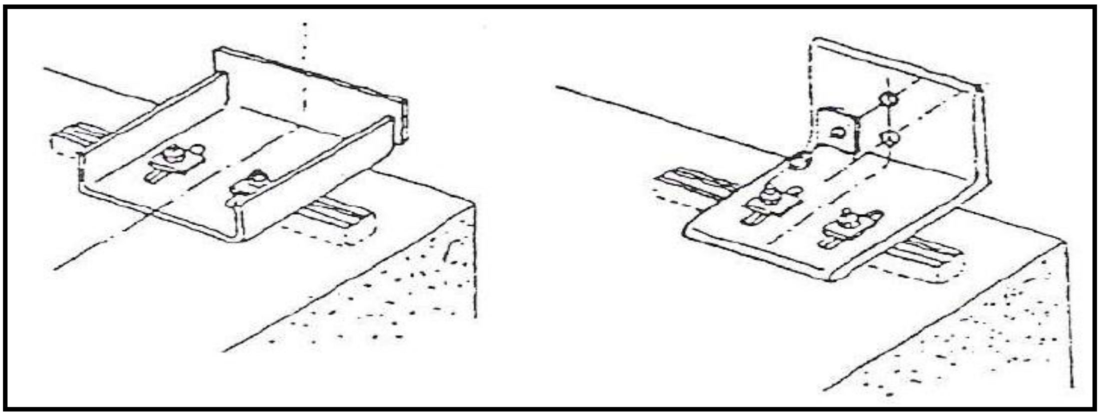


Figure 2.8. The Curtain Wall Bracket Attachment, (Source: www.bcindustries.com)

After the brackets are installed, the panels are lifted from the pallet with mini hoist and suction cups or straps. Then, they are placed on the flatbed trolley and rolled to slab edge for installation, as shown in Figure 2.9 and 2.10.

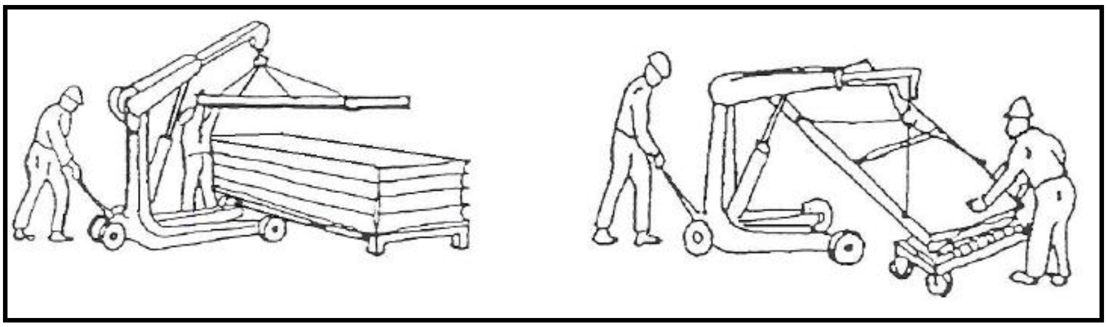
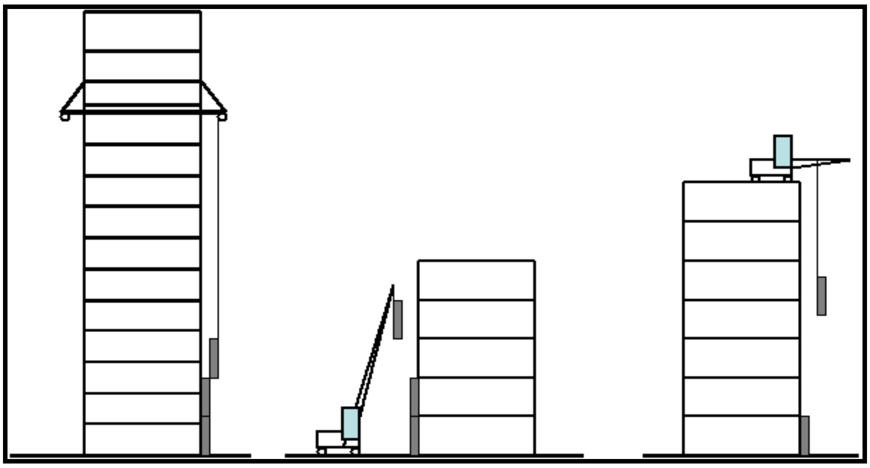


Figure 2.9. The Mini Hoist and Panels, Source: (Source: www.bcindustries.com)

Figure 2.10. The Installation of Panels With The Help of Suction Cups,
(Source: www.bcindustries.com)

Due to the panels are too heavy,they are installed to the facade with the help of lifting cranes as mentioned by CWG (Engineering and Consultancy Services). There are mainly three types of mounting techniques of the unitized curtain wall system which is shown in figure 2.11.



1.Building Around Mobile Crane 2. Ground Mobile Crane 3.Roof Mobile Crane
Figure 2.11. The Panel Installation Diagram (Source: CWG (Engineering and Consultancy Services)

With setting panels on anchorage brackets standing on a slab, the process of installation of the panels is completed. The advantages and disadvantages of this system will be argued later under the subheading of the classification of aluminium curtain wall system.

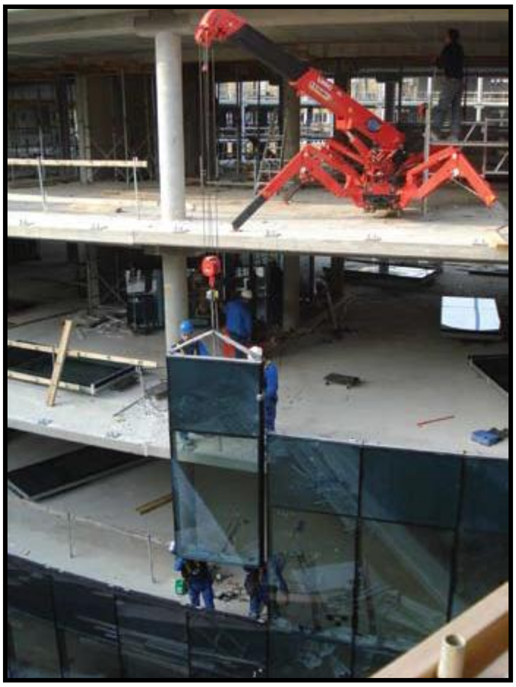


Figure 2.12. The View From Installation Process, (Source: Metal Yapı, İstanbul)

2.3 The Classification of Aluminium Curtain Wall Systems According to Design Method

The classification of aluminium curtain wall sytem can be described under five categories: The Conventional Curtain Wall Sytem (Standart Type, Four-Sided and Two-Sided Aplications), Structural Glazing Sytem, Point-Fixed Glass System, Double Skin Curtain Wall System and Unitized Curtain Wall System (Panel System).

2.3.1 Conventional Aluminium Curtain Wall System

Conventional aluminium curtain wall system is most well known and widely used curtain wall type in architecture. This type of curtain wall is constructed with frame construction technique. Tortu (2006) states that the conventional system called pressure equalization system is developed by Building Technologies Research Institute of Norway in the late 1960s. It is stated that the initial version of this system consists of mullions, transoms, glazing parts with pressure plate and the cover caps. In modern architecture, there are mainly three types of conventional aluminium curtain wall types: standard type, two-sided type and four-sided type.

The standard type of conventional curtain wall system consists of both horizontal and vertical cover caps. The cover cap, which can be produced in various forms and sizes, gives linearity effect to the building facade. Using cover caps in a building facade is the main difference comparing with the other systems. The installation details of standard type are explained by Scott (2009). He mentioned that after the vertical mullions have been anchored to the floor slab, the horizontal transoms are installed. Then, the glass panel and an extruded-aluminium pressure plate put into place. An extruded-aluminium pressure plate, which is intermittently screwed into the mullion, exerts pressure on gaskets to provide mechanically fixing the glass to the frame. Lastly, the cover cap, which is also made up from aluminium, is placed on the pressure plate for concealing fasteners and pressure plate.

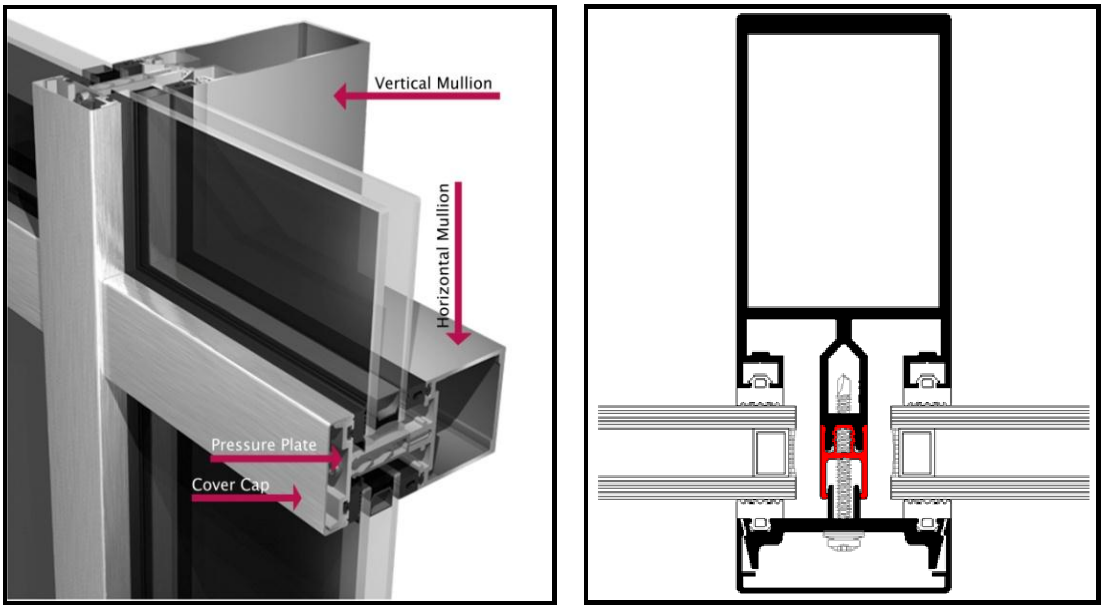


Figure 2.13. The Details From Standard Type of Conventional Curtain Wall System
(Source: Alumil,Curtain Wall Catalog, 2011)

Figure 2.14. An Example of Standard Type of Conventional Curtain Wall System
(Source:Feniş System, 2012)

The other type of conventional curtain wall is called mixed type, which is explained in the curtain wall catalog. (Alumil, 2011). It is stated that cover cap replace with silicone either horizontally or vertically. In this combination, cover cap is used at horizontal direction; silicone is used at vertical direction, or vice versa. So that, there have been different choices for designers and architects according to the aesthetic appearance of facade design.

Figure 2.15. Doğan Medya Center, Ankara
(Two-sided Conventional Aluminium Curtain Wall System) (Source:Alumil, 2011)

The last type of conventional curtain wall system is four-sided type. The four-sided of curtain wall system, which is also called flat face-view construction, is developed within the last years. In this system, the silicone is used similar to structural silicone glazing curtain wall systems in both directions. By the way, the glass wall effect can be achieved.

Figure 2.16. An Example of Four-Sided Conventional Aluminium Curtain Wall System
(Source:Feniş System, 2012)

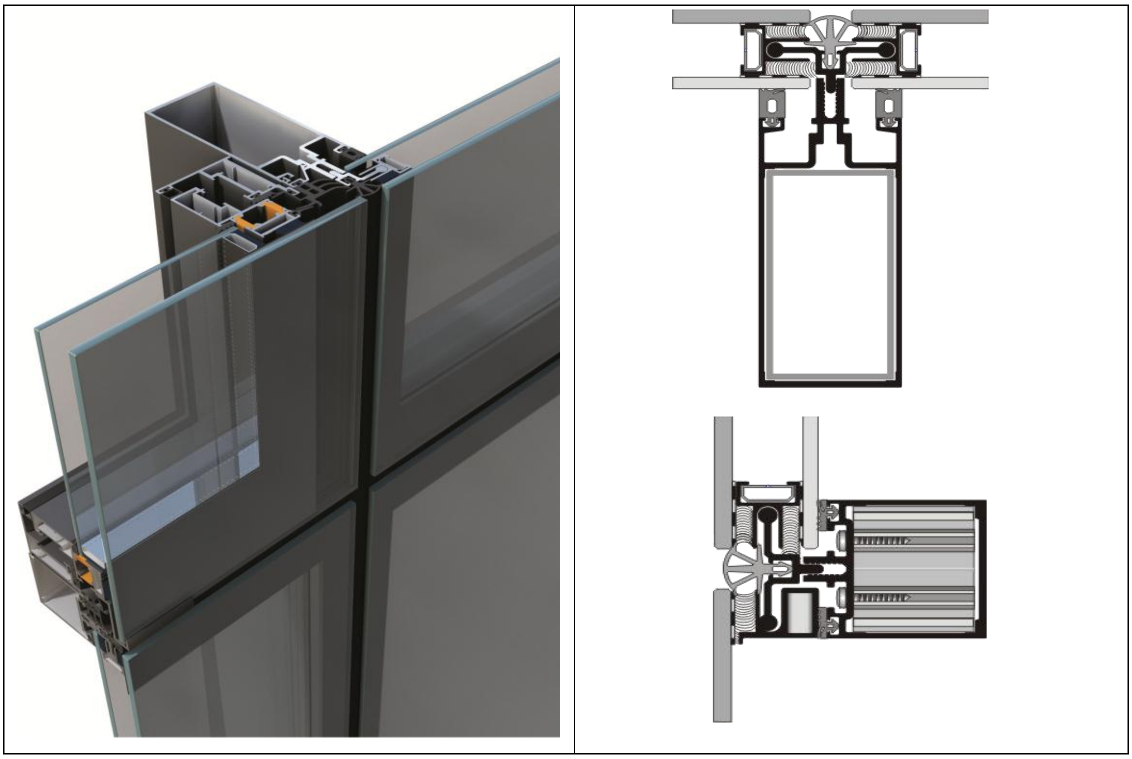


Figure 2.17. The Plan,Section and Axonometric View of Four-Sided Type
(Source: Alumil Technic Catalog, 2011)

2.3.2 Structural Glazing Curtain Wall Systems

Structural glazing curtain wall system, which symbolizes transparency and lightness, is one of the aluminium curtain wall types used especially in high-rise buildings. The construction technique of this system depends on frame construction technique. This system has risen from the conventional curtain wall system by developing glazing and structural details to obtain flat surface appearance. Güvenli (2006) mentions that because the aluminium sections are not seen from the outside view of the facade; the glass effect is achieved which provides aesthetic solutions for architects.

According to Garg (2007), structural glazing is obtained by bonding glass to an aluminium frame through a high-strength and high performance silicone sealant. The adhesive silicone sealant, which is used for bonding the glass to the frame without any necessity of mechanical retention such as beads, clips or bolt fixings, provides tightness of the whole system.

Within this framework, the glazing process is explained by Atalay (2006). First of all, the extruded secondary aluminum frame is prepared. Then, the norton band, which is used to determine the distance between the glass and frame, fastens the glass together with silicone sealant applied to the aluminium secondary frame. For this process, appropriate setting blocks, location blocks and distance pieces are used. Furthermore, it is noted that the surface texture of the frame should be appropriate for silicon sealant. Moreover, factory site should be clean, and air conditioner should be used if there are too many dusts. Furthermore, before the glass panels are carried to the construction site, they should be dried in the factory.

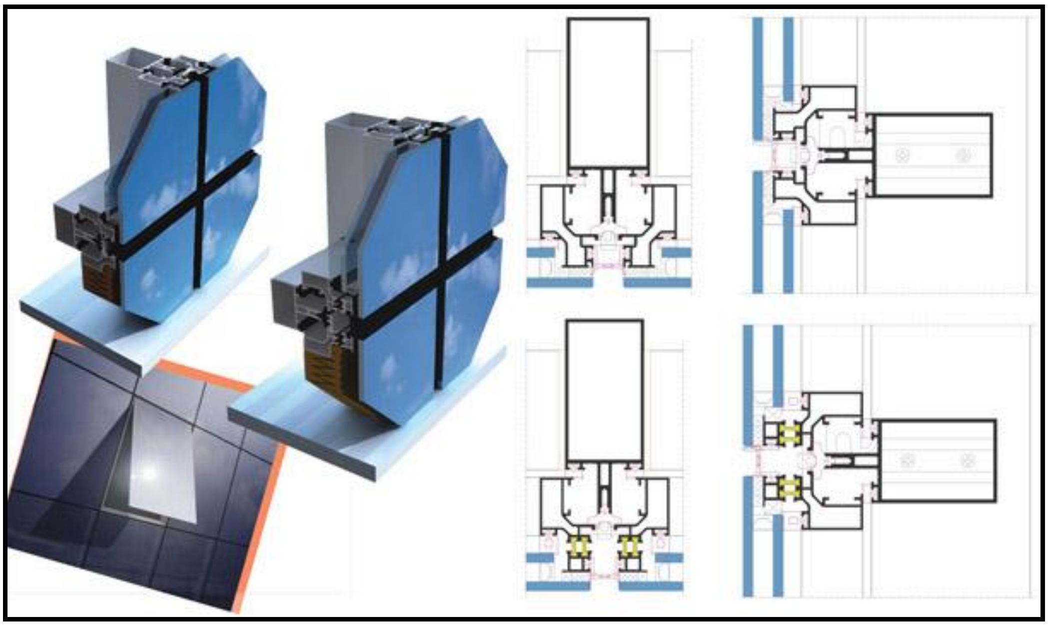


Figure 2.18. The Details and Views of Structural Glazing Curtain Wall Systems
(Source: www.alutech.com.tr,2011)

Figure 2.19. Structural Glazing Curtain Wall Sytem, Westin Hotel, Poland
(Source: Shücco Curtain Wall Catalog, 2011)

2.3.3 Aluminium Glass Curtain Wall System

The innovations in steel and glass industry enable the process of glass curtain wall which is a kind of lightweight curtain wall system. This system is preferable to obtain visual access between interior to exterior by means of transparent property of glass. So that glass curtain wall system is suitable for any renovation projects as a cover of building envelope providing totally transparent effect.

According to Büyükkılıç (2004), glass curtain wall system, which can be coordinated with all types of steel structures ranging from simple pipe columns to those incorporated complex truss systems, are used either vertically or horizontally. In addition to this, the spider fittings are used as point fixed structural system to support the translucent part of the curtain wall system. This is a fully engineered system provides maximum visual access with the minimum structural members.

In this study, glass curtain wall is analyzed under aluminium curtain wall systems. Because, in recent developments, in the aluminium sector, the structural members (horizontal and vertical) of glass curtain wall system are produced with aluminium instead of steel. This is a new trend in modern architecture. Moreover, the spider fittings are beginning to be produced with aluminium material in various colors, as indicated in figure 2.20.

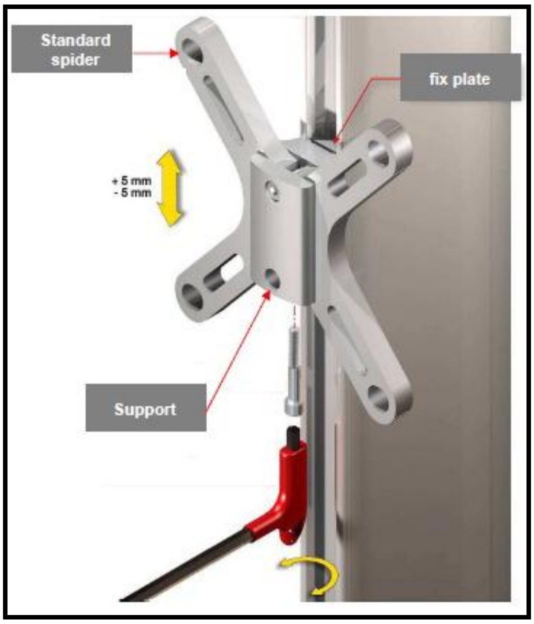


Figure 2.20. The Images of Aluminium Spider Fitting Member
(Source: Alumil Curtain Wall Catalog, 2011)

Previously, the disadvantage of glass curtain wall system was the obligation of using single glazing unit for the transparent part of the cladding. Today, in the light of recent developments, the insulated glass units are beginning to be used for glazing part to provide mainly heat insulation for curtain wall systems.This fact provides opportunities for using glass curtain wall system in wide range of area in construction sector.

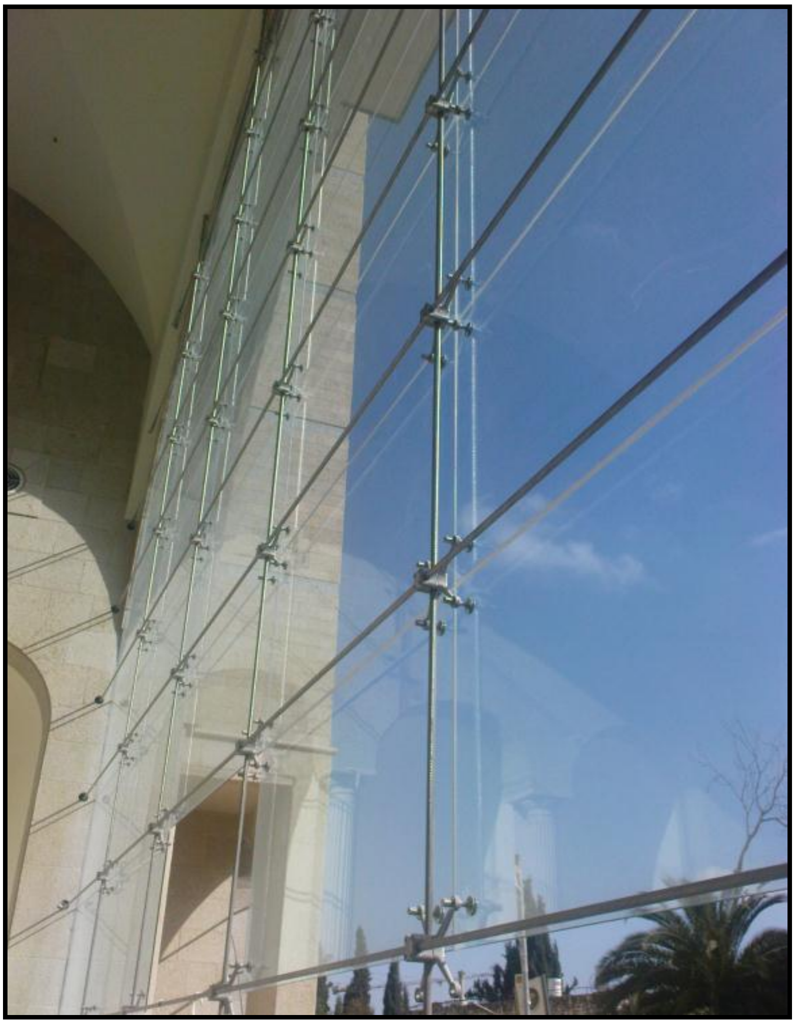


Figure 2.21. The Example of Aluminium Glass Curtain Wall System
(Source: Alumil Curtain Wall Catalog, 2011)

2.3.4 Double Skin Aluminium Curtain Wall System

Double skin facade (DSF), which has started to emerge across Europe, Asia and the United States in the 1980's, have been increasingly considered in terms of saving energy. In addition to this, it provides access to daylight and natural ventilation. Although the early constructions were implemented mostly in low-rise buildings, numerous high-rise applications are seen in the early 1990's.

The basic description and role of the double skin facade is given by Harrison and Boake (2003) quote,

> *"It is essentially a pair of glass skins separated by an air corridor. In this kind of facade, the air cavity situated between the skins is naturally or mechanically ventilated. Devices and systems are generally integrated in order to improve the indoor climate with active or passive techniques. Most of the time such systems are managed in semi automatic way via control systems*."

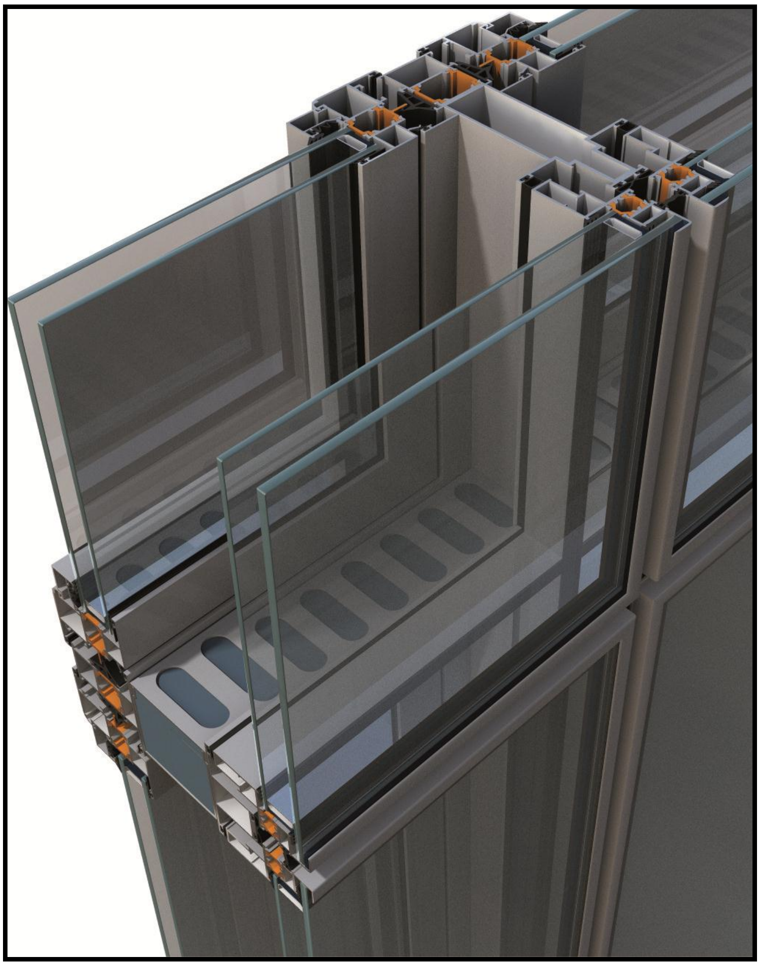


Figure 2.22. Double Skin Aluminium Curtain Wall System
(Source: Alumil Curtain Wall Catalog, 2011)

Within this framework, Arslantatar (2006) mentions that if the double skin facade is designed properly and efficiently, circulation of the air between interior and exterior provides insulated corridor, which is significant for energy efficiency. It is stated that the ventilation of DSF can be mechanical, natural or hybrid (both mechanical and natural). In addition, each DSF is characterized by only a single type of ventilation. Furthermore, it is the mentioned in BBRI Source Book (2004) that the width of the cavity can vary as a function of the applied concept between 200 mm to more than 2m.

According to publication of Enclos Advanced Technology Studio (ATS) (2010), Table 2.1 is a summary of common advantages and disadvantages of double-skin facades cited by different authors. It is mentioned that the most frequently cited benefits of double-skin facades are acoustics and potential of retrofitting. Furthermore, the principal drawback of double skin facades is the increased cost compared to traditional curtain wall systems. As noted in this publication, The Occidental Chemical Center, which is constructed in New York in 1981, is widely recognized as the first modern double skin facade. In this building, the multistory facade reduces the impacts of severe external temperatures by minimizing air infiltration from the cavity to the interior conditioned space so that during the cold winter, the cavity acts as a thermal buffer zone.

Table 2.1. Advantages and Disadvantages of Double-Skin Facade Systems. Review of Multiple Sources (Source:The Report of Enclos Corp's Advanced Technology Studio, İnsight, 2010)

Advantages mentioned by author	Oeserle et al., (2001)	Compagno, (2002)	Claessens et al.	Lee et al., (2002)	B.B.R.I., (2002)	Arons, (2000)	Faist, (1998)	Kragh, (2000)	Jager, (2003)
Lower construction cost (comparing to electrochromic, thermochromic photo-chromic panes)	√								
Acoustic insulation	√			√		√	√	√	√
Thermal insulation during the winter	√	√		√	√		√	√	
Thermal insulation during the summer	√	√		√			√	√	
Night time ventilation	√	√	√	√		√			
Energy savings and reduced environmental impacts						√			
Better protection of the shading or lighting devices	√	√		√					√
Reduction of the wind pressure effects	√	√	√						√
Transparency – Architectural design				√	√	√		√	
Natural ventilation	√	√		√		√	√		√
Thermal comfort – temperatures of the internal wall	√	√		√	√	√	√	√	
Fire escape	√								
Low U-Value and g-value		√				√		√	

Disadvantages mentioned by author	Oeserle et al. (2001)	Compagno (2002)	Claessens et al.	Lee et al. (2002)	B.B.R.I. (2002)	Arons (2000)	Faist (1998)	Kragh, (2000)	Jager (2003)
Higher construction costs	√				√	√			√
Fire protection	√				√				√
Reduction of rentable office space	√								√
Additional maintenance and operational costs	√		√		√				√
Overheating problem	√	√			√		√		√
Increased air flow speed					√				
Increased weight of the structure			√						√
Daylight	√								
Acoustic insulation	√				√				√

The classification of Double-Skin Facade in terms of partitioning of the cavity is explained by Saelens (2002), Oesterle et al., (2001) and E. Lee et al. (2002) as below:

"- Box window type: In this case horizontal and vertical partitioning divide the facade in smaller and independent boxes.
- Shaft box type: In this case a set of box window elements are placed in the facade. These elements are connected via vertical shafts situated in the facade. These shafts ensure an increased stack effect.
- Corridor facade type: Horizontal partitioning is realized for acoustical, fire security or ventilation reasons.
- Multi storey double skin facade type: In this case no horizontal or vertical partitioning exists between the two skins. The air cavity ventilation is realized via large openings near the floor and the roof of the building."

Table 2.2. Advantages and Disadvantages of Box Window, Shaft Box, Corridor and Multistory Type of DSF (Poiraiz, 2004)

	Box window type	Shaft box façade	Corridor façade	Multi-storey facade
Sound insulation	Used both when there are high external noise levels or when special requirements concerning sound insulation between adjoining rooms exist	The fewer openings (compared with the box window type) provide better insulation against the external noise	Problems with sound transmission from room to room	Suitable when external noise levels are high, but problems of sound transmission within the intermediate space
Fire protection	Low risk factor (not any room is linked to each other)	Low risk factor (the rooms are only connected with the ventilation shaft)	Medium risk factor (the rooms of the same storey are linked)	High risk factor (all the rooms are linked with each other)
Natural ventilation –air quality	Openable windows, proper for natural ventilation	Caution should be paid in the way that the airstreams are grouped together from a number of façade cavities into a single shaft	Caution should be paid so that the exhaust air from one room doesn't enter the room above. The problem can be solved with the diagonal configuration	As a rule, the rooms behind multi-storey facades have to be mechanically ventilated

The BBRI, (2004) adds also another type of facade, the Louvers Facades. It is described as:

"with this kind of facade, the exterior skin is composed of motorized transparent rotating louvers. In the closed position, these louvers constitute a relatively airtight facade. In the open position, they allow increased ventilation of the air cavity".

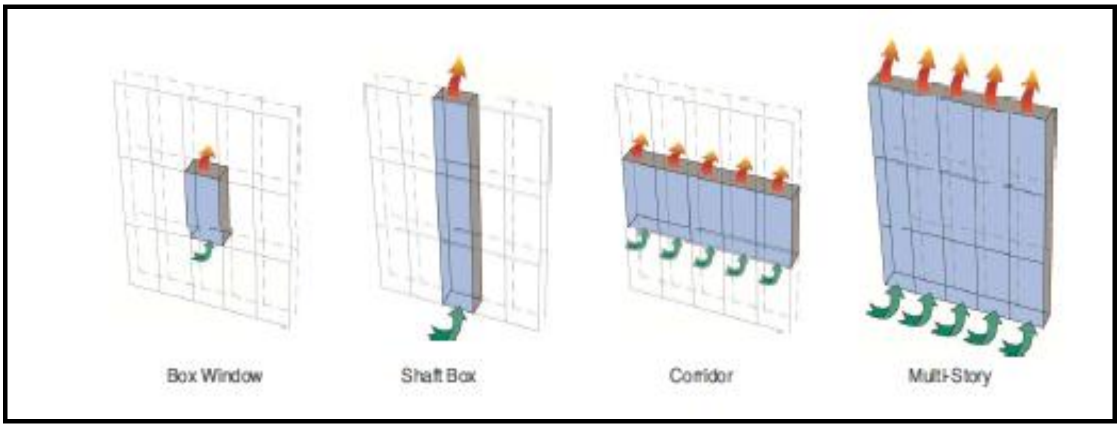


Figure 2.23. Double Skin Facade Configuration, (Source:The Report of Enclos Corp's Advanced Technology Studio, İnsight, 2010)

Poirazis (2006) indicated the most common glazing types used for Double Skin Facades like:

> *"For the internal skin (facade): Usually, it consists of a thermal insulating double or triple pane. The panes are usually toughened or unhardened float glass. The gaps between the panes are filled with air, argon or krypton.*
> *For the external skin (facade): Usually it is a toughened (tempered) single pane. Sometimes it can be a laminated glass instead*."

The behavior under fire conditions is explained by Society of Fire Protection Engineers (2012). It is stated that the concept of double skin facade may causes the fire spread, which previously were not encountered with single skin or more common curtain wall designs. The cavity can act as a shaft of fire and smoke spread, but depending on the cavity design and ventilation scheme, the result may be either an increase or decrease in flame extension and risk of fire spread. So that, it is significant to design the DSF cautiously in terms of fire control.

Today, the double skin facade starts to be used with the different combination of aluminum curtain wall types. Because of this combination, the advantages of the different systems can come together. By the way, the aesthetic visual solutions become variable both inside and outside of the system.

Figure 2.24. The Cavity of The Double Skin Facade
Prisma House, Office Building, Frankfurt, Germany, 2001 (Source:Bayram, A., 2003)

2.3.5 Unitized Curtain Wall System (Panel Curtain Wall System)

A unitized curtain wall system is a kind of light-weight curtain wall system to envelope the facades of a building. The construction technique depends on panel construction technique which is handled in previous section.

According to Scott (2009), unitized curtain wall system consists of prefabricated modules that are assembled under controlled factory conditions and then transferred to the construction site and connected to the preinstalled anchors on the building structure. Although many variations are possible, he mentions that a typical curtain wall unit is between 1.2 to 3 meters wide by one to two stories tall, anchored at each floor slab or beam.

Figure 2.25. The Preassembled Units of Unitized Curtain Wall System (Source: Metal Yapı, 2012)

Figure 2.26. The Preassembled Units of Unitized Curtain Wall System (Source: Metal Yapı, 2012)

According to Patterson (2008) the installation of panel curtain wall units can be applied from the interior of the building. Smaller units can be crated and crane-lifted into the building, and small crews can handle the units, installing them from inside. Alternatively, the installation of the units can be done from the exterior part of the building, as indicated in Figure 2.27. Large units with transportability being the only restriction on size can be factory assembled, shipped to the site, and each unit crane-lifted separately into position on the building exterior. These units can span multiple floors vertically, and be as wide as transport will allow.

Figure 2.27. The Installation of Panel Curtain Wall System from The Exterior of Building
(Source: Metal Yapı, 2012)

Scott (2009) continues that the unitized curtain wall system allows for maximizing factory workmanship and minimizing site workmanship, which provides for the potential of improved quality. Furthermore, it is mentioned that unitized curtain wall is today the system of choice for most curtain wall companies in any large high-rise building project.

Sivanerupan et al., (2008) indicates that unitized curtain wall system provides significant advantages against lateral loads such as wind and building movement. It is indicated that the structural frame around the panel is fabricated as half sections (female and male) for ease of erection and to facilitate relative movement through articulation. Furthermore, the same authors draws attention to the importance of qualified workers for facade assemblage in the construction site. The panels are installed starting either from the bottom or top of the building and going around each floor until the whole building facade is complete. At this point, the manufacturer must rely on qualified workers to ensure that the air seals are properly installed between the vertical mullions in this unitized system.

According to Scott (2009), the advantages of this panel system include greater quality control during fabrication and quicker on-site installation, as well as great ability to accommodate building movement caused by deflection or wind loads. Due to this behavior, the unitized curtain wall system can be called as flexible skin. Through the personal interview with Eray Kaya who is Marmara region sales representative of the aluminium system company, it is stated that especially for extensive surface curtain wall applications, the durability and the maintenance factors become more noteworth, and due the panel curtain wall system consists of prefabricated modules, changing distorted or broken part of the system is easier comparing to stick construction technique. The other advantage of the system is stated that due to any need of scaffold in building construction, the safety of workers is protected at the highest level in unitized curtain wall system, and the minimum numbers of workers are needed because of easier installation stage, which provides cost efficiency. But the square meter price of unitized system is mentioned as still expensive when comparing with conventional and structural silicone systems in Turkey. Furthermore, Scott (2009) states that higher shipping costs and necessity for sequential installation are the disadvantages of the system. Because of the way that one unit interlocks with the next, the units must be installed in a particular sequence; whereas stick systems permit more freedom.

Figure 2.28. The Installation of Units From Bottom to The Top, Esentai Tower
(Source: Feniş System, 2012)

2.4 The Classification of Glazing Types Used in Aluminium Curtain Wall Systems

According to Patterson (2008), architecture is essentially bound up in the play of light, form and space, in this regard, glass is the unique material that opens the interior spaces to play with light. Furthermore, the author mentions that the three most significant visual properties of glass are transparency, translucency and reflectance so that it is difficult to imagine contemporary architecture without glass. All these properties dominate the reason of using glass as a main component of curtain wall systems.

According to Trakya Cam (2012), curtain wall system consists of 80-85 % area of glass and 10-15% area of aluminium frames. So that the appropriate selection of glass types directly affect the total performance of the curtain wall system. Moreover, it is certain that glass industry makes a great progress. There is a wide range of existing and emerging glazing and fenestration technologies in use in the buildings, many of which break new ground with respect to innovative structural use of glass There are basic factors, which include regulation legislation and general concern over such issues as safety, acoustic and energy performance, provides a great demand in growth for architectural glass. With the development of glass industry, different types of glasses are used due to the requirements of buildings. The other selection criteria when considering the choice of glass in a curtain wall system are heat, solar, noise, security and fire control. To make an overview, according to Tortu (2006), glass consists of silica (sand), soda ash, lime and feldispat elements and silica is the most significant element of the total amount. Moreover, glass is not a liquid, but also it is not solid. Glass is between two phases, which is called pisudo-solid.

Atalay (2006) focuses on the importance of the thermal conductivity of the glass in the curtain wall system. The measure of thermal conductivity of glass is called k (U) value and the unit is specified as W/m^2K. In thermal conductivity, conductive heat flow occurs in the direction of less temperature so that in summer the heat flow is from outside to inside; in winter, the heat flow occurs from inside to outside. Higher k value means worse heat control whereas the lower k value means better heat control. In buildings, solar heat can be gained especially from the glazing parts. If the k value of the glass is low, there have been a higher heat gain so that there is an advantage in terms of heating system of the building.

In this study, the main types of glass, which is commonly used in curtain wall, will be handled in parallel with the recent developments in terms of their indicative properties for the selected criteria.

2.4.1 Insulating Glass Types (IGU)

According to Schenider (2008), an insulated glazing unit (IGU) is a multiglass combination consisting of two or more panes enclosing a hermetically sealed air space. The most important function of an IGU is described as reducing heat loss. It provides insulation by preventing heat transfer between the external environment and internal environment. Furthermore, he mentions that panes are connected by a spacer, using sealants to reduce water-vapor penetration. Krynski (2008) states that the space between each lite is either filled with air or an inert gas such as argon or krypton. A balance is needed to achieve optimal results. The same author continues that generally, the gap is between 12 mm to 20 mm depending on the size of the glass and type of gass infill. A cross section of a typical insulated glass unit is shown in Figure 2.29.

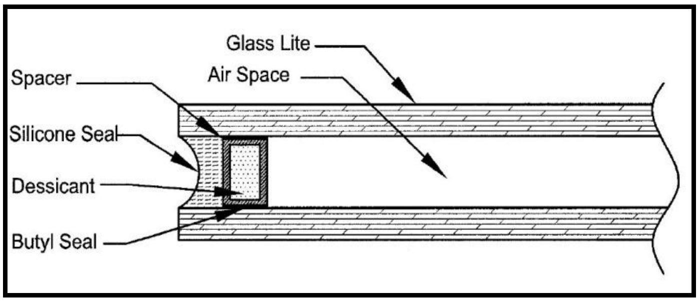


Figure 2.29. A Cross Section of A Typical Insulated Glass Units (Source: Krynski, M., 2008)

According to Garg (2007), heat transferred by conduction and convection due to the temperature difference between outside and inside is reduced to nearly half in case of single glass. The heat-transfer coefficients (U –Values) of glass is explained 2.8 W/m²K for IGU whereas it is 5.73 W/m²K for single glass. Furthermore, it is indicated the insulating glass can help in reducing the exterior noise pollution when unit is made up of glass panes of asymmetrical thickness. He explains that the amount of sound reduction based on the combination of the glass. Using one or both panes of laminated glass help to reduce sound transmission. Moreover, all types of annealed, heat strengthened, tempered or laminated glass seen in Table 2.3.

Table 2.3. Glass Combinations With Specified Gap Distances, Weight and Maksimum Area (Source: www.trakyacam.com.tr, 2012)

Glass Type	Gap Distance (mm)	Maks size (mm)	Maks area (m^2)	Sys. Weight (kg)
3+3	6	1500	1.00	15.5
3+3	9	1600	1.20	15.5
3+3	12	1600	1.40	15.5
4+4	6	1600	1.50	20.0
4+4	9	1800	2.00	20.0
4+4	12	2000	2.60	20.0
5+5	6	2100	3.00	25.0
5+5	9	2300	3.80	25.0
5+5	12	2500	4.20	25.0
6+6	6	2500	5.00	29.0
6+6	9	2700	5.80	29.0
6+6	12	3000	6.90	29.0

The performance of the glazing unit combinations in terms of daylight, solar energy and thermal conductivity is also indicated in Table 2.4.

Table 2.4. Performance Chart of IGU (Source: www.trakyacam.com.tr, 2012)

Product	Thickness	Daylight (EN 410)		Solar Energy (EN 410)					Thermal Conductivity U Value W / m^2K (EN 673)			
		Transmittance %	Reflectance Outdoor %	Reflectance Outdoor %	Absorption %	Direct Transmittance %	Solar Factor	Shading Coefficient	12mm Cavity		16mm Cavity	
									Air	Argon	Air	Argon
Isicam Classic (Clear Float)+ (Clear Float)	4+4	80	14	12	19	69	0.75	0.86	2.9	2.7	2.7	2.6
	6+6	78	14	12	26	62	0.71	0.82	2.8	2.7	2.7	2.6

2.4.2 Coated Glass Types

Increased use of glass in architecture, energy efficiency at the curtain wall system becomes an important concern for architects to demand higher performing products than ever before. Recent developments in glass technology, such as low-emissivity and solar control provide more energy efficiency. There are two main types of coated glass types: Climate Control Glass (low-emissity) and Solar Control Glass.

2.4.2.1 Climate Control Glass Types (Low-emissity)

It is possible to obtain light and heat from the sun by using single glazing units but it is not effective application for heat loss especially in winter. To solve this problem increasing the thickness of glass does not contribute to heat insulation. As a result of intensive studies in glass technology, coated glasses are developed to provide better heat insulation and advanced energy saving at the curtain wall system.

Patterson (2008) states that a more effective coating strategy is the Low-E, or low emissivity coating. Emissivity is partially a measure of a surface’s ability to emit longwave infrared radiation, or heat. Furthermore, it is stated that Low-E coatings are used to reflect radiation, as a result, reducing heat gain or loss by redirecting sun rays. In contrast to the reflective coatings, Low-E coatings have lower reflection and greater light transmission. By the way, it provides not only heat control but also solar control for building envelope.

There are mainly two different applications of low-e coating on the glazing surfaces of curtain wall systems. The first solution is more preferable for cold climates, and the second solution is for hot climates. It is described by Patterson (2008) is that in cold climates, where the need is to retain indoor heat, the coating should be applied to the inner glass, or third surface. Tortu (2006) mentions that this coating provides keeping heat inside and gaining maximum heat and light savings from the sun. Thus, heating costs of the building are reduced. Moreover, this type of coating provides preventing cold zone in front of the window.

It is stated that the coating provides decreasing heat loss by 80% when compared with single glazing and by 60% when compared with float insulated glass units. (www.trakyacam.com.tr)

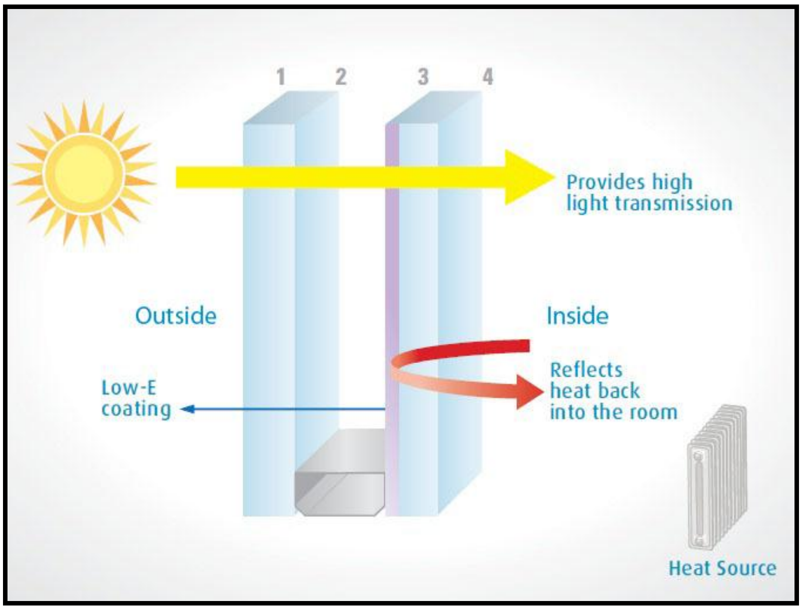


Figure 2.30. The Schema of Low-e Coating for Cold Climates (Source:www.trakyacam.com.tr,2012)

The second application is more appropriate for hot climates. According to Patterson (2008) in hot climates or to keep heat out, the Low-e coating is applied to an outer surface, second surface on insulated glass units. It is stated that this type of low-e coating provides decreasing heat loss by 72% when compared with single glazing and by 45% when compared with float insulated glass units. As a result in winter effective thermal insulation is provided, by the way, heating expenses can be reduced. Furthermore, it provides decreasing solar heat gains by 43% when compared float insulated glass units so that it keeps cooler in summer and cooling expenses can also be reduced. (www.trakyacam.com.tr)

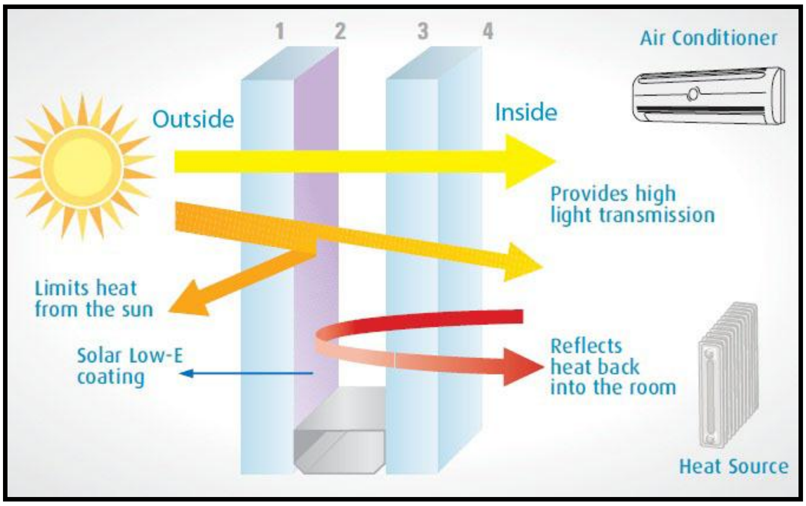


Figure 2.31. The Schema of Low-e Coating for Hot Climates
(Source: http://www.isicam.com.tr, 2012)

2.4.2.2 Solar Control Glass (Reflective)

Reflective solar control glass is widely applied glass type especially used in high-rise buildings. In modern architecture the reflective effect of the facade becomes the symbol of high-rise buildings. According to Patterson (2008), solar reflective coatings, which are a class of coatings with high solar reflection properties, consist of thin, reflective and highly durable metallic layers applied by a process of vacuum (sputtering) deposition. Furthermore, the coatings come in various metallic colors including gold, bronze, silver and others.

The glazing manufacturers indicate that the advantage of this type of coating is the combination of other types of glass units. It can be incorporated into the insulating glass unit with clear float or low-e coated glass. Furthermore, it can be toughened, heat strengthened, and lamination is possible.

The coating can be placed facing outside (surface: 1) or inside (surface: 2) of the building. The difference between these two applications can be described as the reflectance of the glass is emphasized with the first surface applications; color is emphasized with second surface applications. It means that the reflectivity of glass is more distinctive when applied to the outside surface of the glass. The color of the coating can be more visible applied on the second surface application of glass. But it is added that if the coating is exposed to the outside (surface: 1), dirt accumulation on the reflective surfaces is more visible, and cleaning of the glass is required more often regarding the air pollution and the amount of dust in the atmosphere. To prevent this problem, glazing with the coating on the surface: 2 is more recommended. (http://www.trakyacam.com.tr)

The reflective solar glass coating is preferred for mainly aesthetic facade solutions. According to Tortu (2006), with the help of reflecting sunlight, the structural elements such as column, beam, parapet wall and suspended ceiling can be hiding. Thus, homogeneous facade appearance can be obtained. Furthermore, it gives mirror effect for the curtain wall facade and provides a one-way view from inside to outside in the daytime, on the contrary, one-way view from outside to inside at night.
Garg (2007) states that the metal oxide coating of reflective solar glass, which is achieved without affecting the transparency of the glass, helps to reduce heat gain and glare from the exterior. Furthermore, it allows optimum visible light transmission to the exterior. In addition, it is stated that it significantly reduces the cooling load of the buildings.

Figure 2.32. The Image of Reflective Solar Control Glass Source:(http://www.trakyacam.com.tr)

2.4.3 Security Glass Types

There are two main types of security glass types: toughened glass and laminated glass types.

2.4.3.1 Toughened Glass Types (Tempered Glass)

Garg (2007) explains that the tempered glass is an extremely strong glass which is heat treated to uniform temperature of approximately 650Cº and rapidly cooled to induce compressive stresses of 770Cº kg7m² to 1462 kg7m². This process provides to obtain four to five times stronger glasses than single glass of equivalent thickness. Furthermore, Garg continues that tempered glass is difficult to break and when it breaks, it will into small relatively harmless fragments thus minimizing risk of injury. It also provides greater thermal strength and offers increased resistance both sudden temperature changes. So that, it is used to mainly provide safety and strength.

2.4.3.2 Laminated Glass

Glass is a fragile material and has low resistance to impact. By increasing the thickness of glass, its resistance improves but the risks associated with the fragility cannot be prevented. At this point, the term safety means reducing the risk of injury associated with broken glass by accidental impact.

Laminated glass is a safety glass made by laminating two or more sheets of equal or unequal glass thicknesses with a flexible plastic interlayer (called PVB – poly vinyl butyral). Moreover, it is stated that to obtain laminated glass, the glass and interlayer are bonded together by heat and pressure. (http://www.nationalglass.com)

According to Schenider (2008) lamination of transparent plastic film (PVB) enables significant improvements in postbreakage behavior of the glass. If one or both layers of glass are exposed to an impact, the fragments of the glass adhere to the film .Thus any broken pieces of glass remain bonded to the interlayer. He continues that laminated glass elements retain a particularly high structural capacity compared to annealed or heat-strengthened glass. Moreover, lamination can be applied for different types of glass such as annealed, heat-strengthened and toughened.

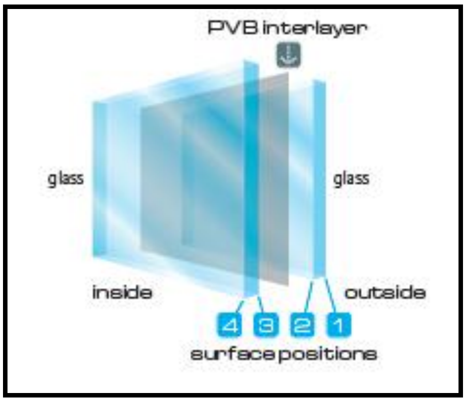


Figure 2.33. Laminated Glass (Source: http://www.nationalglass.com , 2012)

2.4.4 Opacified Glass Types

Opacified glass is commonly used for hiding structural elements such as, column, beam, parapet wall or suspended ceiling. It provides chance for architects to make a composition by opaque and transparent type of glasses. Due to this advantage, it is mostly preferred in a curtain wall design. The application of the enameled coating should be used in the second surface of glass if it is used as a curtain wall system. Furthermore, this type of glass can be used for interior design in a building. (http://www.trakyacam.com.tr)

2.5 The Performance Criteria of Aluminium Curtain Wall Systems

The large surface applications of aluminium curtain wall systems become possible by improving the performance of curtain wall systems due to technological innovations. So that, metal and glass curtain wall systems become widespread on a large scale commercial and institutional buildings. But the design of large surface applications needs extra caution and attention to achieve the thriving building envelope. Basically, the building facade should respond to changing needs over time and provides a high level of safety and comfort. But it is certain that high-rise buildings are exposed to more diverse factors compared to low rise buildings. Within this framework, Atalay (2006) mentions that the facade of tall buildings is exposed to wind effect which increases with building height. So that, the wind load should be handled attentively in curtain wall design. Similarly, the rain has a significant role on the building facade; the differences in the angle of incidence and intensity of rainfall affect the curtain wall system. In addition, the other factors such as noise, facade cleaning and maintenance are also significant. He continues employers demand less construction time and minimum risk in practice. User demands, usage of healthy materials, need of a high level of comfort play an important role in the selection criteria of curtain wall systems. Furthermore, the cost and quality factor are also another determinants.

Regarding this issue, it is critical to control environmental and human sourced factors for curtain wall design. The curtain wall system, act as a filter and protective coat between environment and building, are directly exposed to environmental factors.These environmental factors, which can be defined as main parameters in determining of performance of curtain wall system, consist of heat, water, moisture, fire, sound, wind, and seismic movements. Furthermore, human-sourced factors, which are based on the quality of workmanship and assemblage on the construction site, are directly affect the durability and the performance of the system. Accordingly, not only at the research and development stage but also at the site construction, many precautions should be taken and additional materials are used to increase the performance of the system. Within this framework, the common expectations from any type of curtain wall system, given in Table 2.5 by Schwartz (2001), can be useful and explanatory for understanding the general principles of the systems.

Table 2.5. Various Requirements of Curtain Walls (Schwartz , 2001)

Structural	Support the weight of the wall and transfer lateral loads to the building frame; avoid fracture and yielding
Water	Keep it out
Air	Eliminate excessive infiltration and exfiltration
Condensation	Resist condensation on glass and metal surfaces at interior moisture conditions achievable by HVAC system
Ventilation	Allow for natural ventilation if operable windows are used
Movement	Accommodate differential movement resulting from moisture and temperature movements of materials that comprise the facade
Energy conservation	Resist thermal transfer through radiation, convection, and conduction
Sound	Attenuate noise transmission
Fire safety	Provide rated resistance to heat and smoke transfer while still providing access for firefighters
Maintainability	Allow access to components for restoration and replacement
Constructability	Provide adequate clearances, alignments, and sequencing to allow integration of many components
Durability	Provide the functional and aesthetic characteristics for a long time
Aesthetics	Do all of the above while looking good
Economy	Do all of the above inexpensively

In this study, in addition to human-sourced factors, the environmental factors are explained under five category: Light and Heat Control, Water/Air Moisture control, Fire Control and Wind and Seismic Movement Control.

2.5.1 Light and Heat Control

The efficient light and heat control can be accepted as the main aim of aluminium curtain wall system. Light and heat should be handled attentively for occupants in terms of their comfort and health.Within this framework, the excess and undesirable light and heat can be controlled by clear coating (glazing part) with the help of heat and solar control glasses which is mentioned before. Today especially for glass covered facades, not only heat and and solar control glass but also tempered and reflective glass types are preferred to provide heat and light control. In addition, the types of gases between the panes also have a determined role for the performance of curtain wall systems. According to one of the pioneer glazing company, less conductive and slower-moving inert gases such as argon and krypton begin to replace with dry air. Because they are more efficient to reduce heat and sound transfer from one side of the double glazed unit to the other side. The most popular inert gas used between glass panes is argon gas which is also commonly found in household light bulbs. It is clear, non toxic and non flammable and denser than air. Moreover, the argon gases provides approximately 0.2-0.3 W/m2K thermal conductivity when compared with dry air. So that, it is more preferable for prestigious large scale projects. (www.trakyacam.com.tr)

The other light and heat control method is using aluminium shading elements in curtain wall design. Atalay (2006) states that these shadings can be fixed or moveable (motorized) and movable systems can be manually or automatically controlled. If the sensor is installed on motorized shading systems, the system can be automatically controlled depending on the level of daylight. Furthermore, nowadays photovoltaic and solar panel applications become widespread on building facades. They are integrated into a curtain wall system with the similar technique of glazing system. Solar collectors and photovoltaic panels are used to produce thermal and electrical energy. Moreover, they are also auxiliary for light and heat control.

The aluminium sections are also significant for heat control of the building envelope. In modern architecture, the thermal insulated aluminium profiles become inevitable for heat control by means of thermal break. According to aluminium manufacturers, it is common to use glass reinforced nylon thermal break sections that can be up to 30 mm deep in building facade. Furthermore, in curtain wall system, thermal break slids into grooves and crimped into position by means of rolling the section through specifically designed machines. Although thermal breaks were smaller and made up of pour and fill resin type in the past, today thermal breaks are getting larger to obtain better U values for aluminium sections. Furthermore, Atalay (2006) states that the glazing packers, which is placed in horizontal frames to support the glass, prevent damaging the thermal breaks sourced by the weight of the glass.

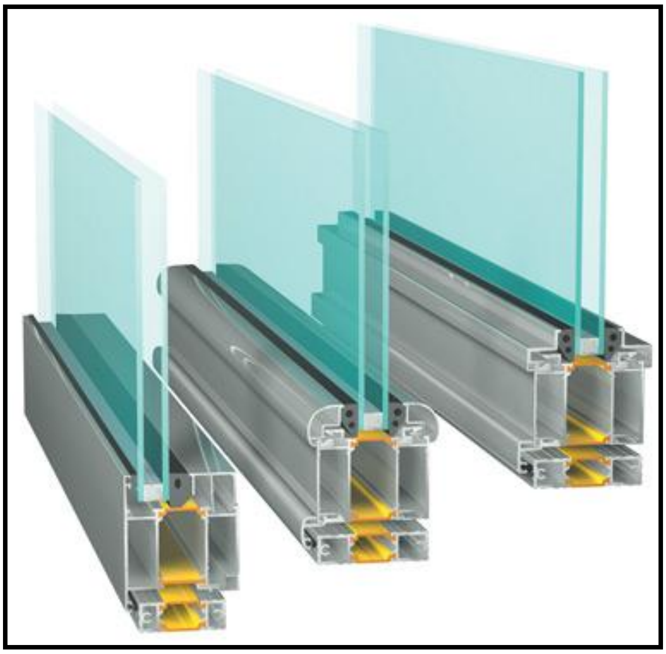


Figure 2.34. Yellow Parts Indicate Thermal Break (Source:http://www.aluminiumdesign.net,2012)

The heat control of spandrel area is also significant for the performance of curtain wall systems. Although there are different combinations for various projects, the ideal expansion of this area from outside to inside can be explained in this sequence: glazing part or aluminium sheet, waterproof membrane, heat insulation material, moisture control membrane and backpan, as indicated in Figure 2.35. Herein, the water proof membrane should allow to transition of water vapour in both direction. In addition, the moisture control membrane is necessary to prevent condensation between the heat insulation and the backpan. Backpan is a kind of metal sheet provides controlling of smoke access between lower to upper story. The heat insulation is generally applied as eps or xps. According to fire regulations implemented in Turkey, if the buildings are classified under high rise building category (Building Height: more than 21.50 m, Roof Level: more than 30.50 m), the heat insulation should be noncombustible. Furthermore, preventing the heat bridge behind the spandrel part of the system, the glazing units are recommended to be used as insulated glazing units instead of single units. This also helps to prevent the burst of the glazing part due to high pressure under spandrel part caused by high temperature storage.

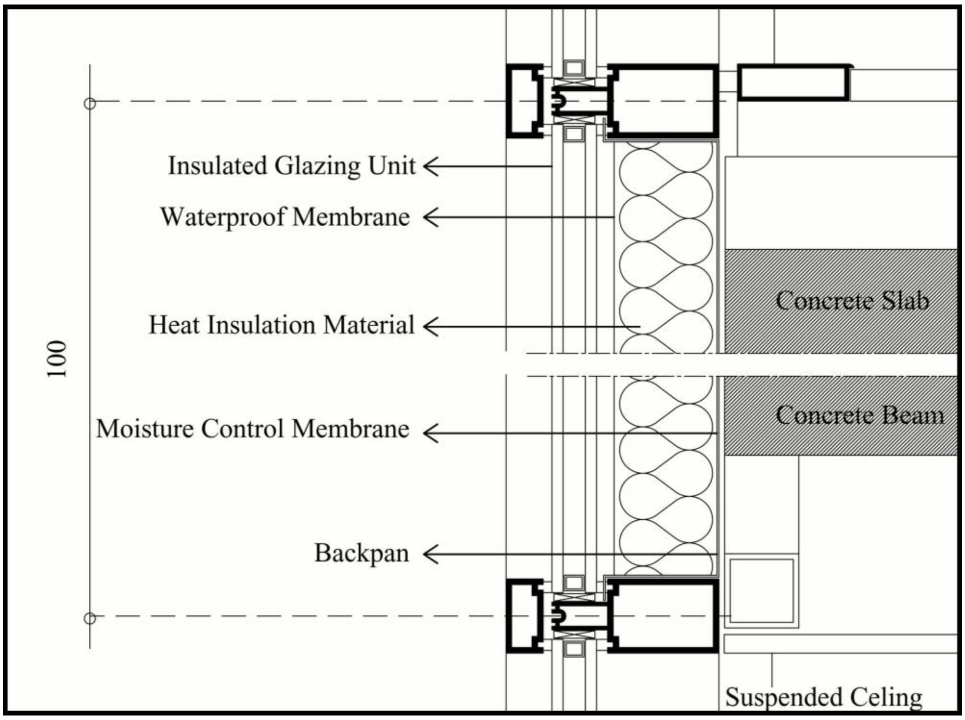


Figure 2.35. The Expansion of Spandrel Area (Source: Individual Archive of The Author, 2012)

2.5.2 Water, Air and Moisture Control

The required and successful aluminium curtain wall systems should provide sufficient control against water, air and moisture. Preventing water penetration is one of the primary focuses when designing and constructing a curtain wall system. Accordingly, the gaskets and sealant materials have a significant role toward water, air and moisture control. Sanders (2006) mentions that a curtain wall is a combination of many elements with two common interfaces between the parts: gaskets and seals. The gaskets and seals provide watertight, flexible connections between the panels and framework. Furthermore, the selection of gasket and sealant material is critical for preventing air and water infiltration; inferior quality can lead to early disintegration and failure.

According to CWCT (2008), it is mentioned that gaskets are primarily required to resist the passage of air or water or both through a joint. Although the gaskets are apparently simple and inexpensive, they are important components in any system against water and air leakage. Moreover, gaskets are preformed components that provide a seal when compressed within a joint. The gasket may be compressed against a mating surface or on another gasket. It is mentioned that the gaskets are divided into two main parts; static and dynamic, as indicated in Figure 2.36. Static gaskets are used to seal joints between fixed components, and dynamic gaskets are applied around opening joints such as windows, doors and access openings. Furthermore, the gaskets are made in a wide range of cross-sections with a range of polymeric materials.

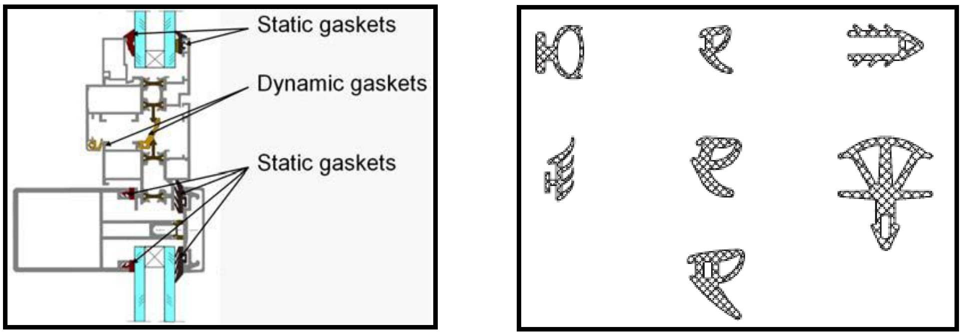


Figure 2.36. Static and Dynamic Gaskets (Source: CWCT, 2008 and Alumil, 2011)

The other way of controlling water and air can be achieved via sealant materials. There are mainly two applications of sealant in curtain wall design: weather seal silicone and structural silicone. The weather seal silicone is widely used at the joints of the system to provide water and air tightness. Within this framework, the critical point is that the material content of the gasket and the silicone should be same to prevent the deterioration of curtain wall systems. Otherwise, the gasket and the silicone can be destroyed over time, which directly affect the performance of the system.

Tortu (2006) mentions that the idea of obtaining a smooth facade appearance without seen any aluminium frames from the exterior on glazing part is provided by the invention of structural silicone which is invented by the Dow Corning company. With this, the non-mechanical method for the attachment of glass and the metal frames is obtained. According to CWCT (2000), structural silicone provides retaining glass without any need for external components therefore it is possible to obtain a smooth facade. The critical point is that the structural silicone should be applied under controlled conditions in a factory and a clean environment and controlled curing times are necessary. As stated by Alpur (2009), the dimension of the silicone is calculated via wind load, the smallest glass dimension and the strength of silicone. Furthermore, it is important to obtain adequate expansion allowance to prevent undesired results, which is caused by thermal changes.

Sanders (2006) states that most of the curtain wall systems comprise condensation drainage provisions, such as condensate gutters, that collect and drain water from the curtain wall to the exterior, is indicated in Figure 2.37.

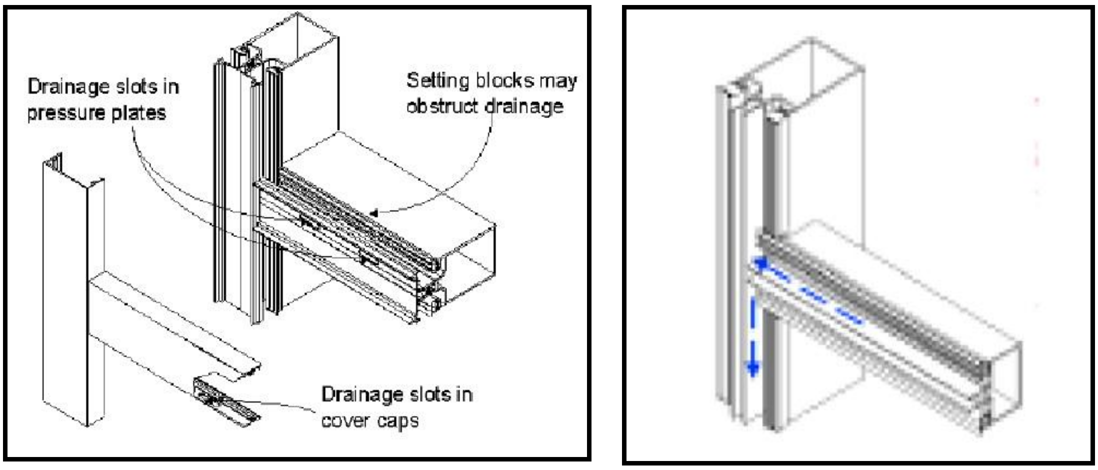


Figure 2.37. Transom and Mullion Drained Curtain Wall (Source: Alumil,2011)

The moisture control is the other significant factor in curtain wall design. An understanding of the causes of condensation, where it occurs, and how to minimize its potential damage is essential. To prevent undesired damages of the moisture, highly efficient vapor barriers should be used in addition to sealants and gaskets. Within this framework, the spandrel walls require careful detailing about moisture control. Winxie (2007) mentions that unless proper moisture control provided, moisture may occur on the indoor face of the wall which may cause serious damage if it is not detected. The anticipated and preventive measures should be incorporated in the wall during construction process. Accordingly, a vapor barrier should be used and if the condensation occurs, it will be collected and drained away.

2.5.3 Fire Control

Fire control is essential for curtain wall system especially in high rise buildings. The building facade act as a stack so that it accelerates the rate of spread of fire and smoke toward the building envelope. Accordingly, the fire regulations and the restrict precautions increase the significance of fire control in a building.

The reaction of materials to the fire has a significance role in fire control. On the basis of their reaction to fire, building materials are classified as non-combustible and combustible building materials. The latter are then classified as non-flammable or normally flammable materials. According to Turkey's Regulation on Fire Protection, the external facades should be constructed with non-combustible materials in high-rise buildings, and for low rise buildings the facade materials must be at least non-flammable.

Kılıç (2012) states that according to Turkey's Regulation on Fire Protection, the composite panels, must be non-combustible, should have an ability for integrity at least 2 hours during a fire. So that, these composite panels should be selected from A1 or A2 class materials. Moreover, not only facade cladding materials but also thermal insulation materials should be non-combustible. Accordingly, rock wool is widely preferred for the insulation material instead of other materials at building facade. The recent fire events at Norvus and Polat Residence in İstanbul increase the attention on materials towards the reaction of fire, are indicated in Figure 2.38 and 2.39. The fire reports which were prepared by the Istanbul Metropolitan Municipality Department of Fire, have indicated that in both cases the fire were sourced from composite panels. It is reported that the interior infill material of the panel was combustible so that with the air circulation, the fire had spread quickly.

Figure 2.38. The View From The Fire In Polat Tower, Şişli,İstanbul.
(Source:www.hurriyet.com.tr,16.07.2012)

Figure 2.39. The View From The Fire In Novus Rezidence, Ataköy, İstanbul, (Source:www.hurriyet.com.tr, 25.09.2008)

Fire resistant zone and the spandrel area are also significant factors for fire control. Kılıç (2012) mentions that spandrel area or fire resistant partition, which prevent direct contact with the window and the flame, is necessary in order to prevent the fire passage from one floor to another floor if the fire is sourced from the interior part of the building, which is indicated in Figure 2.40. As shown in Figure 2.41, at least 50 cm length fire resistant partition is should be needed for preventing the passage of flames to the upper floors. He continues that in high-rise buildings, the height of the spandrel area is generally 100 cm. Because of the spandrel area, flame spread can be controlled to a certain extent, but it is not prevented completely. For this reason, the sprinkler system is compulsory for high rise buildings. According to Turkey's Regulation on Fire Protection, if the fire sprinkler system is applied, spandrel wall is not obligatory for fire control.

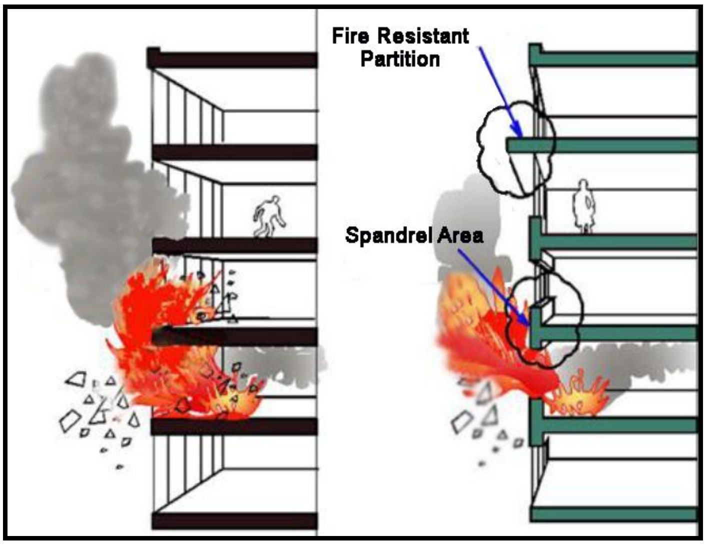


Figure 2.40. The Transmission of Fire With and Without Spandrel Area. (Source:Kılıç, 2012)

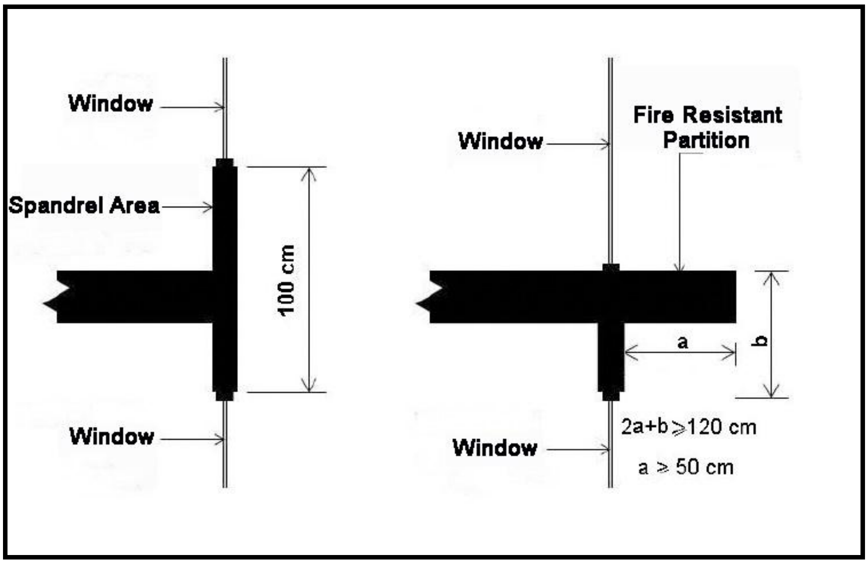


Figure 2.41. Fire Resistant Partition and The Spandrel Area (Source:Kılıç, 2012)

The other issue is the use of the smoke seal for fire control. According to Atalay (2006), the curtain wall system is constructed 20-25 cm far away from the parapet wall. The void space between the structural floor and curtain wall introduces a risk of fire in terms of spreading fire from one floor to another floor. Within this framework, the smoke seal, is applied both over and under the parapet wall, is essential to slow down the passage of fire and combustion gases and smoke seal has an L - section usually made up from 2 mm galvanized steel. Moreover, the sound impermeability can be provided with insulation materials applied on the smoke seals in spandrel area.

2.5.4 Wind and Seismic Movement Control

The wind factor plays an important role in curtain wall design especially for high-rise buildings. The properties of aluminium frames and glazing types and other detail solutions are determinants in terms of durability, safety and functionality of the building. According to Atalay (2006), the wind load, which is significant for the selection of curtain wall glazing types, is specified in standards in accordance with the height, location, geographical position and geometry of the building. In special cases, the dominant wind value should be specified according to the regional meteorological records and the accounts must be calculated through these values. He continues that the dominant wind load is calculated through the results of 50-year observation period of regional data. Furthermore, the wind load whose unit is N/m^2 or Pascal, is basically used to specify the thickness of aluminium members for curtain wall design. According to wind load calculations, the maximum deflection of the curtain wall profile is designated as effective span length (L) / 200 or 8mm for aluminium sections.

Seismic performance of the system during an earthquake is the other important criteria for curtain wall system. Especially in seismic zones, as well as the measures are taken for the building structural system, the measures should also be taken for curtain wall applications. Accordingly, the appropriate detail solutions should be developed for building facade to prevent undesired damages. Basically, glass breakage is a big threat to people's lives in an earthquake. Within this framework, Arnold (2009) handles the behavior of glazing part and aluminium frames under seismic load. It is stated that the glass is fragile to forces which is applied to its edges and corners by rigid framing members. During an earthquake, the structural system tends to drift. So that, a typical curtain wall, in which the framing is rigidly attached to the structural framing system, deforms. Thus, the glass has broken and the aluminium frames are distorted, is indicated in Figure 2.42 and Figure 2.43.Concerning this issue, Atalay (2006) mentions that in order to prevent glass damages, the aluminium system members should allow the movements of glass in both horizontal and vertical directions. So that, the glass panels should be supported with both fixed and hinged supports by special anchorage members to the structural system. Thus, the risk of fracture and breakage on the connection between aluminum profiles and connection points can be controlled. Regarding this issue, Arnold (2009) mentions that it is significant to maintain the adequate clearances between the aluminium frames and glass to allow for this movement. Furthermore, it is stated that glass is retained within the frame by flexible gaskets, and the clearance between the glass and frame is maintained by inserting small rubber block spacers. These flexible gaskets and rubber spacers allow for considerable movement of the glass within the frame, and the rubber blocks must be compressed before the glass affects the metal.

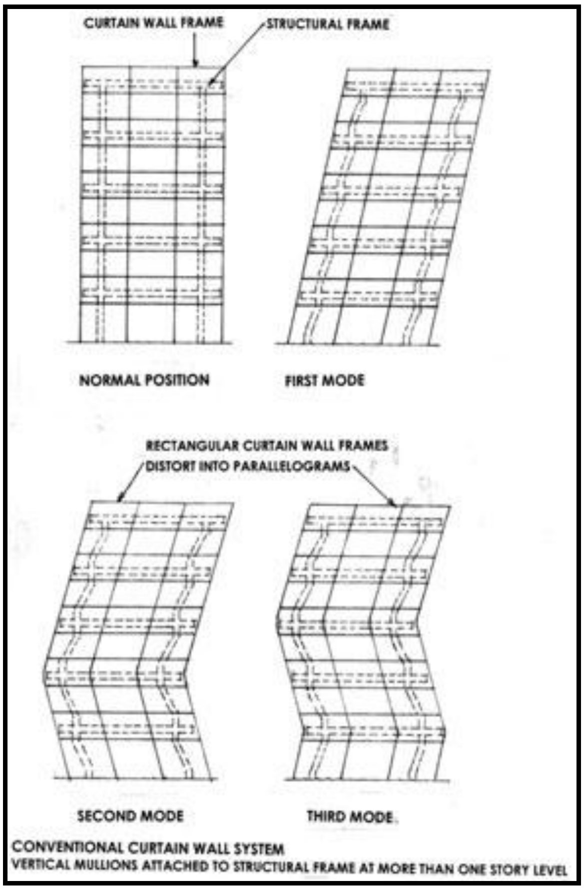


Figure 2.42. Vibration Modes of a Typical Building Frame and Its Relationship to Curtain Wall (after Brueggman et al. 2000). (Source:Arnold,2009)

Figure 2.43. Glass Damage in Mexico City Earthquake, 1985. (Source:Arnold,2009)

The design of aluminium section is also determinant to minimize earthquake damages in curtain wall design. With the development of facade technology, the members of aluminium curtain wall system can be produced lighter to reduce the weight of the curtain wall system. Tığ and İrtem (2006) explains the significance of reducing the total weight of the system and states that if the load of the building members is reduced, similarly, the seismic load acting on a building declines. Furthermore, with smaller aluminium sections, more economical solutions can be obtained. For this reason, the optimum cross-section of aluminium sections becomes even more important for building construction. In addition, it is important to achieve the most economical solution with maximum safety and adequate rigidity for manufacturers and system designers. So that, in Turkey, the German Norms (DIN 1055-4, DIN 4113-1, DIN 4108, DIN 4109, etc.) are used to dimension the system members and to identify the system insulation performance by the aluminium system manufacturers .Moreover, the Turkish Standards (TS EN 755-2, EN 755-5, TS 1164, TS 4926, TS 5247 etc.) are used to specify the properties and cross section sizes of the aluminium members especially by the system designers.

When considering the seismic performance of curtain wall system types, Atalay (2006) declares that the details in stick system cannot bear those seismic loads. The panel or semi panel system is more successful to allow horizontal and vertical movements under seismic loads so that they exhibit better performance during an earthquake. Because the individual panels can act together with building structural system and they can tolerate the impact of earthquake loads.

2.5.5 Human Sourced Factors

No matter how successful facade system is, the installation and workmanship quality totally affect the overall performance of the system. For this reason, at least the research and development studies, the factory production and installation quality at the construction site is important in terms of performance of the system.

The human sourced factors can be listed as the quality of workmanship on construction sites, usage phase and fabrication factors. The reality is that at most of the buildings, there are significant installation problems sourced by lack of inspection of workers. Poor workmanship directly affects the performance of curtain wall systems. So that, the precautions should be taken to decrease the faults in workmanship. Moreover, the most critical parameter is the use of deficient materials in terms of gaskets, sealants etc. at the installation stage of curtain wall system. For instance, in figure 2.44, there is a problem with the connection of horizontal and vertical members in a curtain wall system. There should be a gasket to tolerate extension and shortening of horizontal members at different temperatures .Otherwise, there is a critical risk for bending of horizontal members. In this example, the gasket between horizontal and vertical members is missing, which directly affect the performance of curtain wall systems.

Figure 2.44. The Fault In The Horizontal and Vertical Connection of Aluminium Members. (Source:Individual Archive of The Author, 2012)

According to Atalay (2006), to increase the performance of the curtain wall system, fabrication and installation process should be quick, and physical conditions on the construction site should be applicable for working during the day. Furthermore, the aluminium system components should be stored in construction site to decrease duration of the installation period.

2.6 The Performance Tests of Aluminium Curtain Wall Systems

Today, the performance of curtain wall systems is measured by various test methods. These tests are both preferred by system manufacturers at research and development stage and curtain wall contractors at construction stage. These tests are implemented by authorized company on various sizes of the specimen. The dimension of the specimen varies according to test methods. Furthermore, performance facade tests are implemented through the principle of confidentiality. The system details, performance tests results and the materials are confidential and privileged information between the system developers and the facade testing company because these tests reveal the pros and cons of the applied curtain wall systems. Şenkal (2005) states that performance tests provide examining of curtain wall systems before the manufacturing process with their actual size in accordance with international standards. So that it is identified how the performance of the system in the building is. Moreover, the tests enable the elimination of problems during the usage period. The same author continues that when the systems succeed the performance tests the system can be accepted to be fulfill in terms of water penetration, static strength, air permeability, seismic performance etc.

The commonly used performance tests, which are static air permeability, static watertightness, dynamic air permeability and water spray, water penetration under dynamic pressure, wind resistance, building movement, site tests, are explained below with respect to related norms. In addition to them, the acoustic performance, impact resistance of glass, component cycling tests are also conducted on the curtain wall systems in Turkey.

2.6.1 Static Air Permeability Test

Static air permeability test is widely used curtain wall tests. In Turkey, the test is implemented through TS EN 12152 (2004), TS EN 12153 (2006) and TS EN 13116 (2004). The TS EN 12152 (2004) describes the performance requirements and classification criteria; the TS EN 12153 (2006) defines the air permeability test method. During the test, the positive and negative pressures are applied to the sample respectively. Applied positive pressure means that an outer face is subjected to a higher pressure than inner face. The negative pressure is vice versa.

The working principle of the system can be explained that the sensors on the apparatus of the system measure the flow rate of the air passing through the channel. If there is an air leakage, the air pressure starts to decrease. So that the system tries to regulate the air pressure. Herein, the amount of air passing through the channel gives the amount of air leakage.

According to TS EN 12153 (2006), at the beginning of the static air permeability test, three pressure pulses are applied to the specimen. These pressure pulses are determined as a greater value from 500 Pa or %10 more of maximum test pressure. For each pressure pulse, the maximum level should not be achieved in one second and these pressure pulses should not be applied more than three seconds. Then the different pressure levels are implemented to the specimen for both positive and negative pressures. The pressure levels begin from 150 Pa to maximum pressure level at intervals of 150 Pa.

The air permeability performance of the fixed parts of the specimen is explained in the same Turkish norm. First of all, the air permeability of test room without any effect of the specimen is measured. It means that all vertical and horizontal parts of the specimen are covered with tapes and made airtight for insulation. This value is called Qc. Then the tapes are removed apart from additional parts which means the surrounding of the specimen. The various pressure levels are applied to the specimen and the result is called Qfc. Finally, the Qc value is subtracted from Qfc value. Thus the air permeability of fixed part is calculated.

If the specimen consists of openable parts, the air permeability performance is calculated in this sequence. Firstly, openable part is insulated with tapes in order to ignore its effect. Furthermore, the only additional parts of the fixed parts are insulated. Thereafter, the various pressure levels are applied to the sample. The result is called Qfc. Secondly, the tapes on openable part are removed. The pressure levels are applied again. The result is called Qtc. Finally, the Qfc value is subtracted from the Qtc value. Thus the air permeability of openable part is calculated. (TS EN 12153, 2006)

After the positive and negative tests are conducted, the classification is done in with respect to TS EN 12153 (2006) in order to evaluate the performance of the specimen. The maximum pressure levels, maximum air leakage value and the classes are shown in Table 2.6 and 2.7. If the classification is calculated according to the overall area of the specimen, the maximum air leakage shall be 1,5 $m^3/h.m^2$. In addition to this, the maximum air leakage is determined as 0,5 $m^3/h.m$ if the classification is based on fixed joint length. The class types are accepted as A1, A2, A3, A4 and AE for different pressure levels. As mentioned TS EN 12152 (2004), if the sample has many parts divided by horizontal and vertical members, it is necessary to classify the sample according to fixed joint length method.

Table 2.6. Air Permeability Measurements Based on Overall Area. (Source: TS EN 12152, 2004)

Maximum Pressure P max (PA)	Air Leakage $m^3/h.m^2$	Class
150	1,5	A1
300	1,5	A2
450	1,5	A3
600	1,5	A4
>600	1,5	AE

Table 2.7. Air Permeability Measurements Based on Fixed Joint Length.(Source: TS EN 12152, 2004)

Maximum Pressure P max (PA)	Air Leakage $m^3/h.m$	Class
150	0,5	A1
300	0,5	A2
450	0,5	A3
600	0,5	A4
>600	0,5	AE

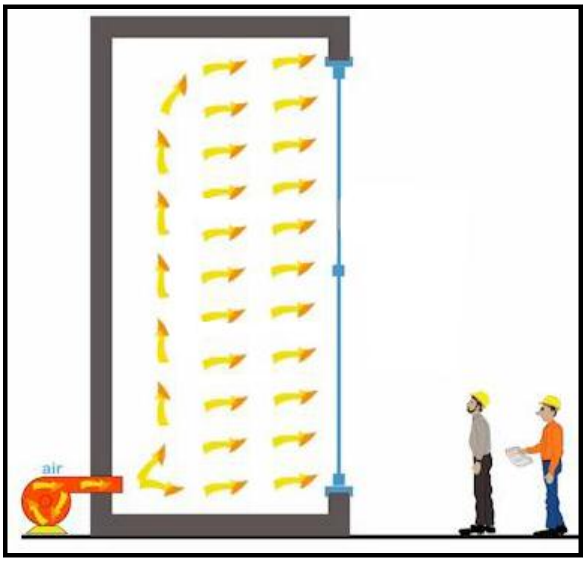


Figure 2.45. Schematic Diagram of Static Air Permeability Test
(Source: Facade Testing Institute, 2012)

2.6.2 Watertightness Laboratory Test Under Static Pressure

The watertightness laboratory test under static pressure is performed in accordance with TS EN 12154 (2004) and 12155 (2005). The TS EN 12154 (2004) describes the performance requirements and classification criteria of the test; the TS EN 12155 (2005) defines the static watertightness test method. The water is applied to the specimen as soon as the test is began and the sample is subjected to positive test pressure during the test. The water pressure begins at 0 Pa during 15 minutes and then 50 Pa, 200 Pa, 300 Pa and 450 Pa pressure levels are implemented during five minutes. Thereafter, the followed pressures are applied at the interval of 150 Pa up to maximum test pressure.

The working principle of the system is that the outer surface of the specimen is subjected to predetermined positive test pressure during specific time intervals with a constant flow of water in order to form a continuous water layer. During the test, test engineer observes the specimen whether there is a water leakage or not. If there is any water leakage, the observer stops the water penetration test and notes and reports both the location and the quantity of water leakage. (TS EN 12155, 2005)

According to TS EN 12155 (2005), in order to perform this test, a water flow rate of 2 L /m².min is required. The water layer is adjusted by special nozzles. The angle of water spraying from the nozzles is determined by standards as between 90° and 120°. An example of static watertightness test apparatus is shown in Figure 2.46.

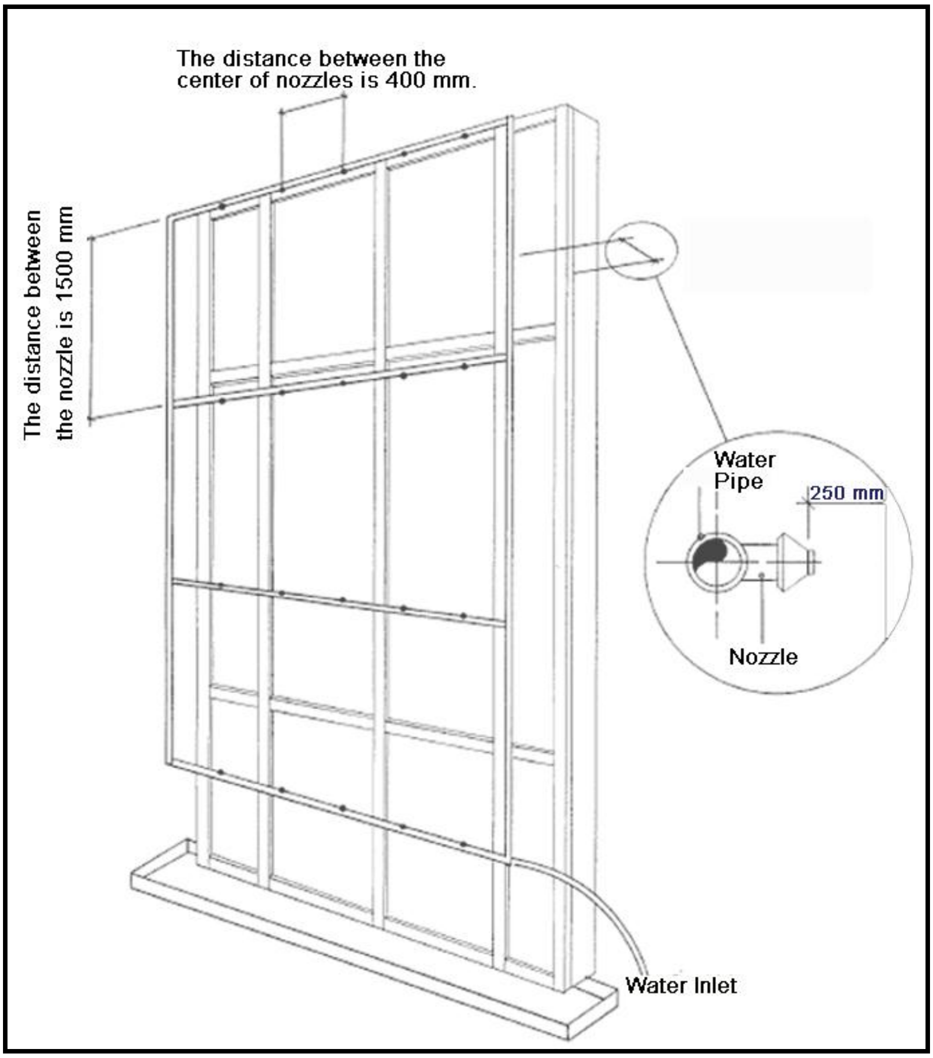


Figure 2.46. An Example of Static Watertightness Test Apparatus. (Source: TS EN 12155, 2005)

After the test is completed, the sample is classified through its performance as R4, R5, R6 , R7 and RE categories which is indicated in Table 3.3.

Table 2.8. The Classification Charts for Static Water Penetration Test (Source: TS EN 12154, 2004)

Class	Pressure Steps in (Pa) and Test Duration in Minutes (Pa /min)	Water Spray Rate L/min m²
R4	0/15; 50/5; 100/5; 150/5	2
R5	0/15; 50/5; 100/5; 150/5, 200/5; 300/5	2
R6	0/15; 50/5; 100/5; 150/5; 200/5; 300/5; 450/5	2
R7	0/15; 50/5; 100/5; 150/5; 200/5; 300/5; 450/5; 600/5	2
RE xxx	0/15; 50/5; 100/5: 150/5: 200/5: 300/5: 450/5: 600/5; above 600/5 in steps of 150 Pa and 5 minutes duration	2

Table 2.8 (Continued)

The Highest Test Pressure (Pa)	Class
150	R4
300	R5
450	R6
600	R7
>600	RE xxx

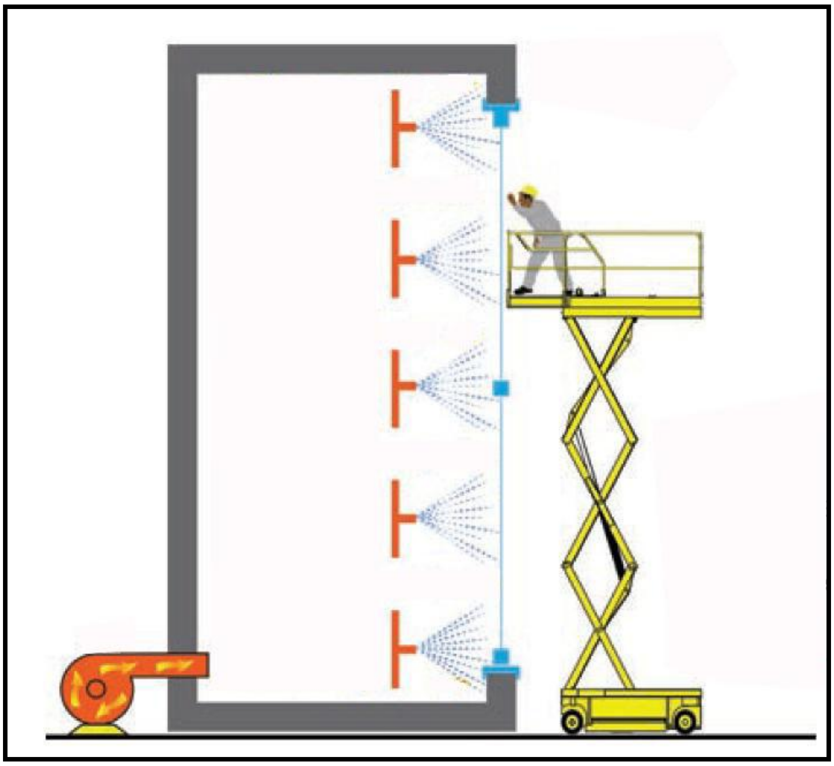


Figure 2.47. Schematic Diagram of Static Watertightness Test
(Source: http://fti-europe.com , Retrieved November, 2012)

2.6.3 Dynamic Air Permeability and Water Spray Test

This test is used to examine for both air permeability and watertightness performance of the curtain wall test. In Turkey, this test is conducted through TS EN 13050 (2011). The working principle of the system is shown in Figure 2.48. This test is implemented via special fan and nozzles whereas the static watertightness test is conducted only with nozzles. In dynamic test, there are water sprayed nozzles which are capable of spraying 2 to 500 liters of water per minute. The water is thrown to the test sample by means of wind speed which is produced by wind produced fan. During the test, test engineer observes the specimen whether there is a water leakage. If there is any water leakage, the observer stops the test and the location of water leakage is reported. (TS EN 13050, 2011)

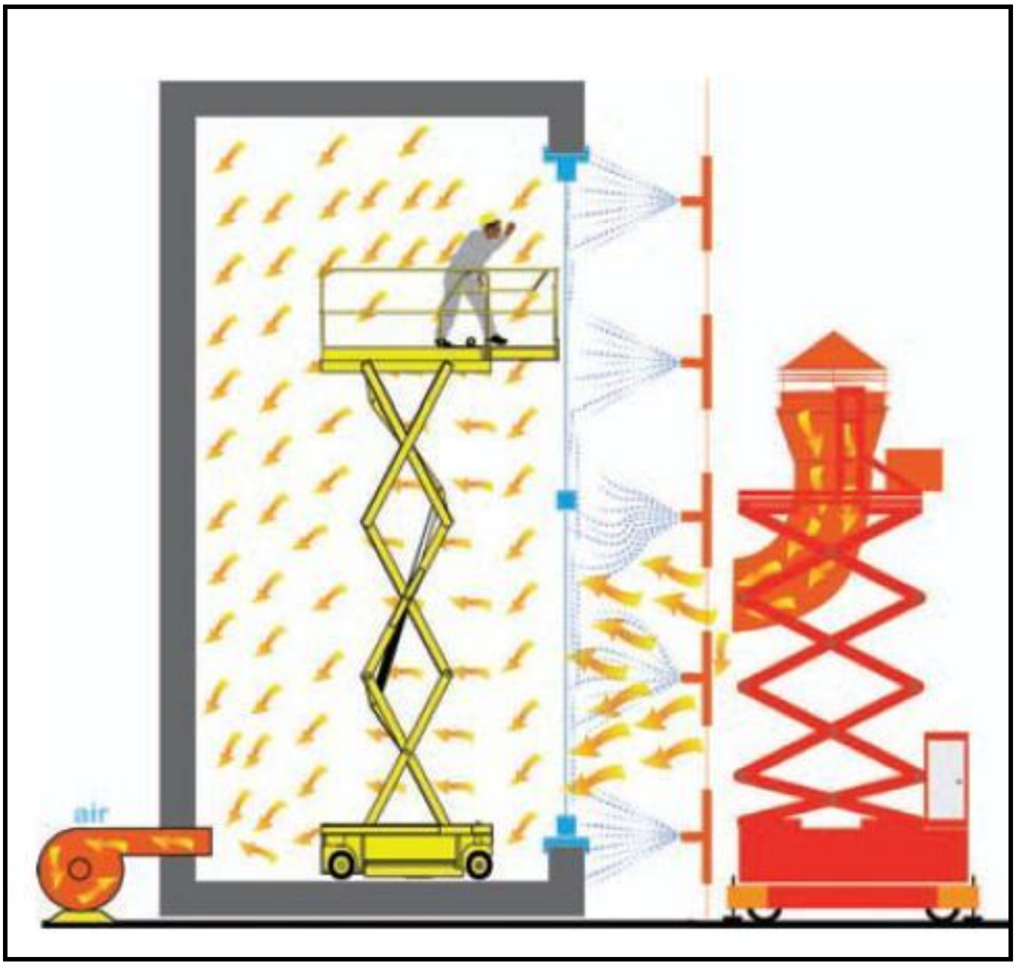


Figure 2.48. Schematic Diagram of Dynamic Air Permeability and Water Spray Test
(Source: http://fti-europe.com , Retrieved November, 2012)

Figure 2.49. The Photo Taken from The Dynamic Air Permeability and Water Spray Test
(Source: http://fti-europe.com , Retrieved November, 2012)

Figure 2.50. The View From Wind Produced Fan
(Source: Individual Archive of The Author, 2012)

2.6.4 Water Penetration Test Under Dynamic Pressure

This test is similar with dynamic air permeability and water spray test. The main difference is using airplane engine instead of wind produced fan. The air plane engine generates wind speed which helps to throw the water to the test specimen, shown in Figure 2.51. This test is applied through AAMA 501-1(2011). According to this norm, the diameter of the air plane should not be less than one-half the greater dimension of the curtain wall area to be tested although it is not required to be more than 4100 mm. In addition, if the test sample is not very large, the airplane is located in front of the vertical mullion and it is directed from top to bottom. But if the sample is large, it is necessary to place and direct the airplane for all vertical mullions. At the end of the test, according to observation of test engineer, if there is any water leakage, it is recorded and added to the report. Herein, the water leakage is described as any uncontrolled water that appears on any normally exposed interior surfaces, which is not contained or drained back to the exterior, or that can cause damage to adjacent materials or finishes.(AAMA 501-1, 2011)

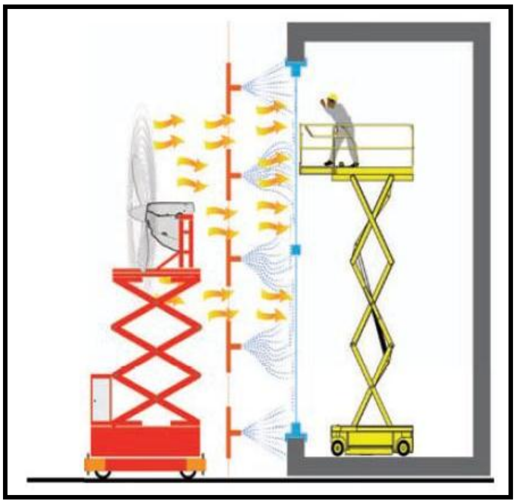


Figure 2.51. The Working Principle of Water Penetration Test Under Dynamic Pressure
(Source: http://fti-europe.com, Retrieved November, 2012)

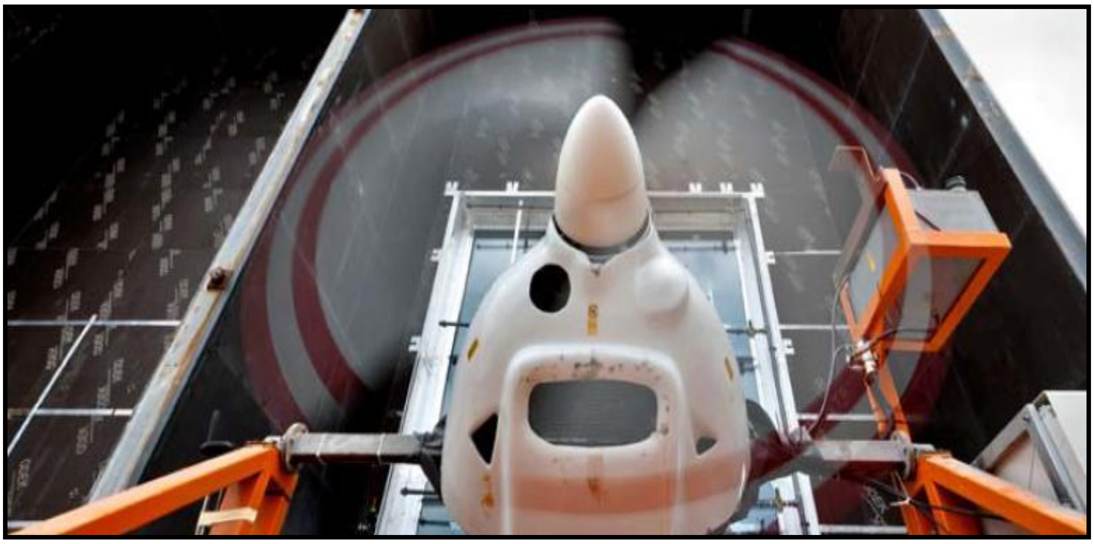


Figure 2.52. The View From Air Plane Engine
(Source: http://fti-europe.com , Retrieved November, 2012)

2.6.5 Wind Resistance Test

The wind resistance test is a widely preferable test method especially for high rise buildings. In Turkey, the test is conducted through TS EN 13116 (2004) and EN 12179 (2000). TS 13116 (2004) describes performance requirements; TS EN 12179 (2000) specifies the method to determine the performance of both fixed and openable parts of the curtain wall under positive and negative static air pressure. In wind resistance test, positive test pressure is conducted before negative test pressure.

Before the tests, if there is an openable parts in a curtain wall test specimen, they are opened, closed and locked five times. Then, the displacement of the vertical members caused by wind pressure is measured by three position sensors. These position sensors are used to measure the displacements of vertical member of sample in horizontal direction under positive and negative pressure. These sensors are placed on top, bottom and middle fixed points of the vertical member in order to used motion control. But for wind resistance test, the only linear displacement can be measured with the help of these special devices.

The test procedure is described in TS EN 12179 (2000). At the beginning of the test, three pulses of air pressure as 50% of design wind load or 500 Pa whichever is greater is applied. Then, the sample is subjected to 25%, 50%, 75% and 100% of design wind load.

After different values of design wind loads are applied to the sample, the frontal displacements at each test pressure is specified and frontal deflections are determined with the help of position sensors. If required, 150% of the design wind load, which is called safety load, is applied as a positive test pressure for a minimum of 15s ± 5s. After the positive test pressure is completed, it is time to implement negative test pressure. The negative test pressure is applied to the sample with the same procedure of positive test method.

At the end of the tests, frontal displacements of the members are calculated through the values taken from the sensors. The value taken from the sensor from the middle is subtracted from the average of the bottom and top sensor summation. Then, the results are graphically expressed. Herein, it is significant that the frontal displacements should be smaller than L (Floor Height) mm / 200 or 15mm, whichever smaller is accepted. At the end of the test, the performance class of the sample is determined. (EN 13116, 2004).

2.6.6 Building Movement Test

In Turkey, there are two different methods for measuring the performance of the curtain wall system in terms of building movement; static and dynamic. The static test method is conducted through the AAMA 501.4 (2009), the dynamic test method is applied in accordance with AAMA 501.6 (2009). These tests provide evaluating the performance of curtain wall systems when subjected to specified horizontal displacements as an earthquake or a significant wind event. Furthermore, it is intended to analyze the seismic safety of architectural glass components within a curtain wall. There is a difference between the test apparatus of static and dynamic tests. The static test is applied on the same test chamber with air permeability, watertightness and wind resistance tests although the dynamic test is performed on an individual test apparatus.

If the sample is subjected to water penetration, air permeability and wind resistance tests, the static building movement test is selected for analyzing the behavior of the specimen under a seismic event. After conducting a static movement test, the other applied tests are repeated. The aim is to evaluate how the performance of the curtain wall changes in terms of water penetration, air permeability and wind resistance after implementing horizontal movements via static building movement test. But if the aim of the test is to evaluate the only seismic performance of the specimen apart from other performance criteria, the dynamic building movement test is implemented to the specimen.

For both static and dynamic tests, there are moveable and stable steel beams. The bottom and top horizontal members of the specimen are fixed to the stable beam of the test apparatus.The middle horizontal member is anchored to the moveable steel beam which acts on the horizontal direction (x direction). The working principle of the system based on directing the moveable steel beam and observing whether there is any failure such as glass breakage, separation on the fittings, distortions at the corners or other damages in the specimen.

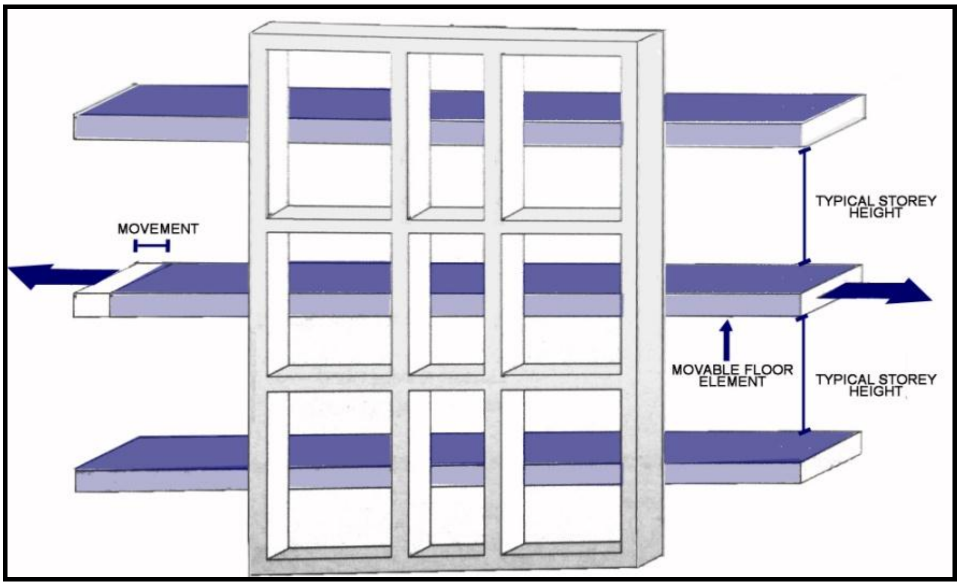


Figure 2.53. Typical Test Specimen Configuration (Source: AAMA 501.4, 2009)

According to related standards, each test consists of three full cycles. Herein, a cycle is defined as a full displacement in one direction then back to originating point, full displacement in the opposite direction and finally back to the originating point. For both tests, the design displacement is determined by the special specifier. At the end of the test, the test engineer observes whether there is a disengagement on the connection points, sealants or glazing failure, metal distortion and permanent deformation. If there is a failure, the observer stops the test. If the cause of the problem is not detected, the test is repeated.

According to AAMA 501.6 (2009), in dynamic test, the calculation is conducted indepented from the floor height. For all projects, the steel beam is moved ± 75 mm in 0.8 HZ and ± 150 mm in 0.4 Hz respectively, as shown in Figure 2.54. But the static test is calculated according to the story height. In this test, the displacement is determined by this formula: 0.010 x the greater of the adjacent story height. (AAMA 501.4, 2009)

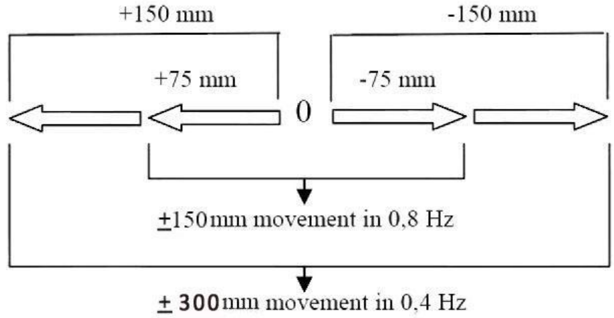


Figure 2.54. The Movement and Displacement Schema of Dynamic Building Movement Test
(Source: Facade Testing Institute, 2012)

Figure 2.55. The View From Dynamic Building Movement Test
(Source: http://fti-europe.com, Retrieved November, 2012)

2.6.7 Site Tests

There are mainly two tests applied on building site in terms of watertightness and air permeability tests. In addition, the sound insulation test can also be applied to special projects. But the other tests such as wind resistance, building movement etc. have not performed yet in the construction area in Turkey.

A water permeability test is applied according to EN 13051 (2001) and AAMA 501.2-03 (2009). The water is sprayed from the outside of the curtain wall system and the water leakage is observed from the interior of the curtain wall system. In American norm, there is a single nozzle directed on horizontal and vertical members, which sprays a constant volume of water during 5 minutes. According to EN 13051 (2001), there are three stable nozzles, which placed on a 1 meter long plastic pipe water line, creates continuous water flow on the curtain wall specimen.

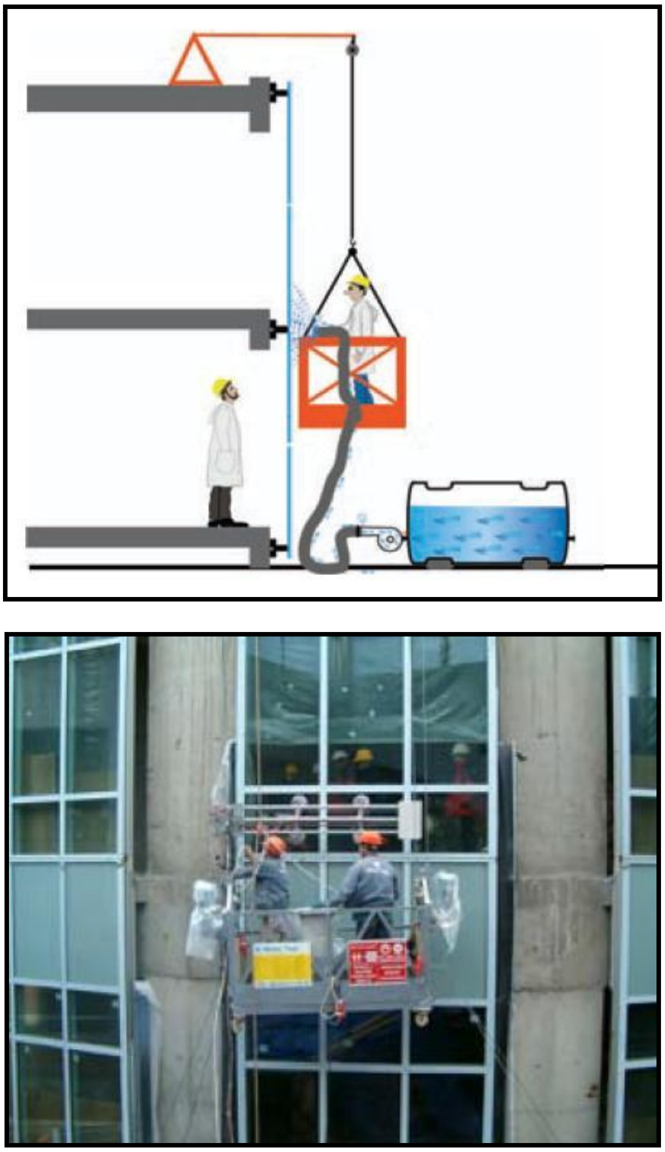


Figure 2.56. The Photo and Schematic Diagram of Watertightness Site Test
(Source: http://fti-europe.com , Retrieved November, 2012)

CHAPTER 3

MATERIAL & METHOD

This chapter describes the details of the material and method which are used to conduct the study. First is presented as “Material.” The method of the study and analysis are presented under subheadings.

3.1 The Material

At the beginning of this study, the facade test centers locating in Turkey were investigated and the communication with these companies was provided by mobile phone or e-mail. The main aim of this study, applying specified facade tests on aluminium panel curtain wall system in order to evaluate the system, was explained to the facade test centers and it was asked how they can help through conducting this investigation. One of the facade test center has responded positively of the demand of the author and in accordance with the invitation of Murat Seyhan who is the general manager of the facade test center, the author has gone Istanbul in three times in order to have a meeting. At the end of these meetings, it was decided that because of limited time, instead of conducting individual tests for this study, one of the planned panel curtain wall system test reports could be used without giving the name and the details of the project. For this purpose, the manager of the facade test company has taken permission for attending the author on one of the panel curtain wall performance tests which would be implemented in the soonest time. The facade tests were planned to be conducted at April 2012 for one of the construction company. The design features of this project and the date of planned tests were acceptable according to the aim of this investigation. For this project, in order to analyze the performance of the panel system, the specified facade tests were conducted on the mock-up of aluminium panel curtain wall system at facade testing factory by authorized company in Çatalca, İstanbul. The mock-up belonged to one of the prestigious office towers in İstanbul. The building, which is under construction, is planned to be 170 meter height.

Before conducting curtain wall tests, the initial test report, which is called as a method statement of testing, was prepared by facade testing company. This report has consisted of the general information about the test arrangement and test apparatus. In addition to this, the sequence of planned tests, the performance criteria about the test method, test date and reference standards were explained in this report. According to this initial test report, the performance curtain wall tests in terms of air permeability, watertightness, wind resistance, and building movement tests were conducted on specified date and time. During the performance tests, through the personal interview with Öner Arslan who has been the test engineer of facade testing company, the information about the facade tests were gathered. After the facade tests were completed, the test reports, which were used to analyze the performance of the curtain wall system, were prepared by the same company. These test reports have comprised the information about the name and address of the test agency, completion date of the test and date of issuance of the report. In addition to this the detailed drawings and photos of the specimen, aluminium system types, glass thickness, method of glazing type were added to this performance report.

Within this framework, in this section, the mock-up of aluminium panel curtain wall system and the aluminium curtain wall performance tests were given.

3.1.1 The Mock-up of Aluminium Panel Curtain Wall System

The mock-up of the panel curtain wall system was prepared by aluminium company. Before a day from the date of the curtain wall tests, it was carried to the facade testing factory. It was significant that all parts of this specimen shall be totally consistent with the project details in terms of its size, materials, types of glass, anchorage details and method of construction. So that, the sample was checked whether it was totally same with the described features according to its architectural project. During the day, the workers of the aluminium company installed the specimen to the test chamber carefully. The critical point was to conduct the proper installation of the sample to the test chamber. Herein, the balloon gasket, which was the interface between the test chamber and the specimen, had an important role in the performance of the specimen.

The dimension of the specimen was 3000 mm to 7600 mm in other words it was two story height through its architectural project. In order to evaluate the performance at the intersection points of the different modules, the mock-up consisted of the details of the combination of different modules at the borders.The glass combination of the mock-up was defined as 8mm + 16 Air Gap + (6mm+1,52 PVB+6mm). In addition, the mock-up was composed of only fixed parts. As mentioned before, the specimen belonged to tall office towers. Due to being high-rise building, there were not any openable parts such as windows in curtain wall design of this project. It is planned that the building will be ventilated mechanically. In this study, the other details and drawings of the specimen are not shared due to confidentiality.

After the installation process was completed, the sample was ready for performance curtain wall tests.

Figure 3.1. The Specimen and the Test Chamber
(Source:Individual Archive of The Author,2012)

3.1.2 Aluminium Curtain Wall Performance Tests

In this study, the performance of panel curtain wall system was evaluated with the help of facade tests. These tests are significant and valuable applications for curtain wall design in order to obtain safety and functional building envelopes. These conducted tests were determined through the demand of the project owner and the aluminium company. Herein, the determinant factor was the height of the building. Due to this project belonged to high-rise office towers, not only air permeability and watertightness performance, the wind resistance and the building movement performance was also demanded. So that, for this project, the air permeability, watertightness, wind resistance and static building movement test were planned to conduct to the sample.

3.2 The Method

The method of this study composed of two main parts. Firstly, the preliminary process for curtain wall tests is handled. Then, the application process of curtain wall tests are described.

3.2.1 Preliminary Process For Curtain Wall Tests

In order to implement performance tests, well-planned preliminary process is necessary. For this study, first of all, the test chamber was prepared. Test chamber, which was made up from steel and plexiglass materials, consisted of a well insulated control and mechanical room, as indicated in Figure 3.2 and 3.3. In the control room, there were computers to record and monitor data during the tests used by test engineers. In addition, the temperature of the test chamber was arranged between 10° to 30° and the relative humidity was measured between 25% to 75%. These conditions were preserved from four hours before to the end of the test.

Figure 3.2. The Photo From The Control Room.
(Source: Individual Archive of The Author, 2012)

Figure 3.3. The Photo From The Mechanical Room.
(Source: Individual Archive of The Author, 2012)

Secondly, the equipments and the machines were checked and verified to obtain the accurate results.Within this framework, the test engineer Arslan quote,

> *"….Herein, the calibration of the machines which were used for the facade testing is significant. The significant point in the calibration is to specify parameters which cause the uncertainty for the measurement. Then, determinant parameters are calibrated separately. For each six months, the devices are checked and the data are recorded. If there is %10 percentage of variation between the test results, the improvement work is applied to the system. If it is necessary, the authorized company is called to inspect the improvement process of the devices."*

Figure 3.4. The Equipments for Installation of The Specimen.
(Source: Individual Archive of The Author, 2012)

After equipments and the machines were controlled, the sample was gathered and installed to the test chamber. Finally, the mock-up of panel curtain wall system was ready for performance tests.

3.2.2 Application Process of Performance Curtain Wall Tests

The sequence of the performance curtain wall tests, which was presented in the method statement of the report, is really important to get better results. These tests were determined by the facade testing company according to the demand of aluminium company and the contractor of the project. First of all, static air permeability, static watertightness and wind resistance tests were implemented to the sample. Then, the static building movement test was applied. Thereafter, the static air permeability and static water penetration tests were repeated in order to evaluate how the performance of the sample changed after building movement test was applied.The application process of facade tests was completed within 8 hours. The watertightness test continued for an hour but the other tests could be completed in almost 15 minutes. In addition, the facade tests were performed in complying with the TS EN 13830 (2005). The sequence of the tests and related references were as below:

Test 1: Static Air Permeability Test:
In accordance with TS EN 12152 (2004), TS EN 12153 (2006)
1.a) Under Positive Pressure
1.b) Under Negative Pressure

Test 2: Watertightness Laboratory Test Under Static Pressure:
In accordance with TS EN 12154 (2004), TS EN 12155 (2005)

Test 3: Wind Resistance Test:
In accordance with TS EN 12179 (2000), TS EN 13116 (2004)
3.a) Under Positive Pressure
3.b) Under Negative Pressure

Test 4: Static Building Movement Test:
In accordance with AAMA 501.4 (2009)

Test 5: Static Air Permeability Test:
In accordance with TS EN 12152 (2004), TS EN 12153 (2006)
5.a) Under Positive Pressure
5.b) Under Negative Pressure

Test 6: Watertightness Laboratory Test Under Static Pressure:
In accordance with TS EN 12154 (2004), TS EN 12155 (2005)

CHAPTER 4

RESULTS & DISCUSSIONS

This chapter consists of three main parts. In the first part, the results and discussions related the aluminium curtain wall tests which were applied on panel curtain wall system were presented. Herein, the results of the facade tests were analyzed under four main topics; static air permeability test result, static watertightness test result, wind resistance test result and building movement test result. In the second part, the facade performance tests and the suggestions for their improvements was given. In the final part, the advantages of panel construction technique in comparison to stick construction technique was handled.

4.1 The Results of The Applied Performance Tests

In this part, the results of applied curtain wall tests, which are static air permeability, static watertightness, wind resistance and building movement, are given. Accordingly, the pressure design value of the this sample was given as 2915 Pa and the pressure extreme value was measured as 4373 which was the %150 of pressure design value.

4.1.1 Static Air Permeability Test Result

The first test conducted on the panel curtain wall system was static air permeability test. Herein, the air permeability means passage of air through the sample when subjected to positive or negative air pressure. According to TS EN 12153 (2006), at the beginning of the test, the three pressure pulses were applied to the specimen. These pulses were determined to be the greater one of the two values; 500 Pa or 10% more of maximum test pressure. For positive and negative air pressures, maximum test pressure applied to the specimen was defined as 600 Pa. So that, 660 Pa, which is greater than 500 Pa, was implemented to the specimen. Thereafter, different pressure levels from 50 Pa to 600 Pa were applied to the specimen. Each of following pressure levels were conducted to the sample during 10 seconds. Finally, the test was completed and the results were given below for positive and negative air pressure tests based on overall area and fixed joint length.

Table 4.1. The Performance Table of Air Permeability Test Based on Overall Area

POSITIVE PRESSURE			
ϕ1 / ϕ2	Test Pressure (Pa)	Air Leakage (m^3/h)	Air Leakage ($m^3/h.m^2$)
ϕ1	50	2,99	0,13
ϕ1	100	4,27	0,19
ϕ1	150	4,85	0,21
ϕ1	200	6,26	0,27
ϕ1	250	7,15	0,31
ϕ1	300	6,85	0,30
ϕ1	450	10,60	0,46
ϕ1	600	10,81	**0,47**

NEGATIVE PRESSURE			
ϕ1 / ϕ2	Test Pressure (Pa)	Air Leakage (m^3/h)	Air Leakage ($m^3/h.m^2$)
ϕ2	50	1,70	0,07
ϕ2	100	3,33	0,15
ϕ2	150	4,43	0,19
ϕ2	200	5,55	0,24
ϕ2	250	6,75	0,30
ϕ2	300	7,44	0,33
ϕ2	450	9,83	0,43
ϕ2	600	12,15	**0,53**

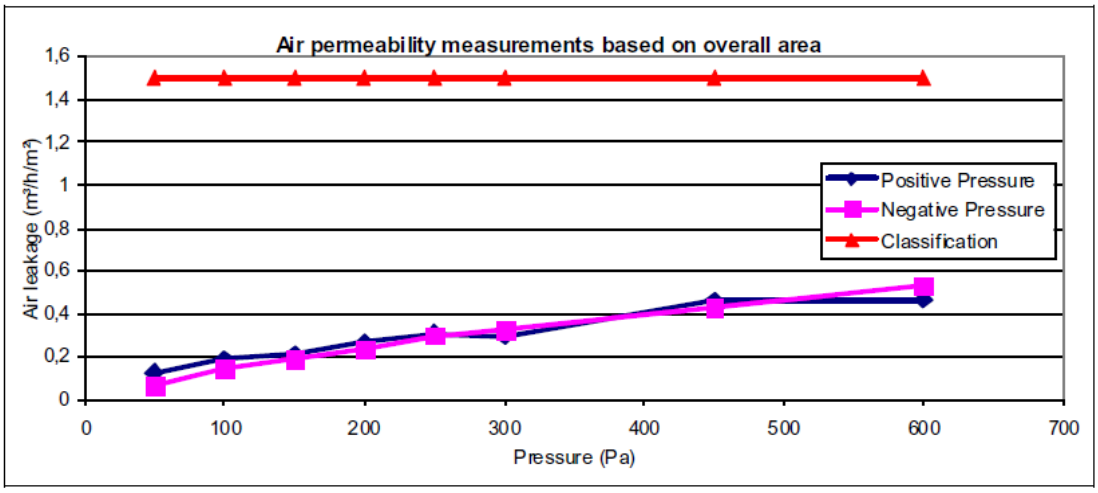


Figure 4.1 The Graph of Air Permeability Measurements Based on Overall Area.

The results of the test were evaluated in accordance with TS EN 12152 (2004). According to this norm, the value of maximum air leakage should be 1,5 m³/h.m² when the air permeability measurement based on the overall area of the specimen. In this test for 600 Pa, the result was calculated as 0,47 m³/h.m² under positive air pressure; it was measured 0,53 m³/h.m² under negative air pressure. The both results are smaller than the 1,5 m³/h.m² which was the maximum air leakage limit determined in TS EN 12152. So that, the performance of the specimen was accepted as successful based on gross area. In addition, according to test results, it is seen that the performance of this sample was more successful under positive air pressure comparing to negative air pressure.

The static air permeability performance was also analyzed in terms of meter length of joint. The results of air permeability measurements based fixed joint length is indicated in Table 4.2.

Table 4.2. The Performance Table of Air Permeability Test Based on Fixed Joint Length

.

POSITIVE PRESSURE			
ϕ1 / ϕ2	Test Pressure (Pa)	Air Leakage (m³/h)	Air Leakage (m³/h.m)
ϕ1	50	2,99	0,07
ϕ1	100	4,27	0,10
ϕ1	150	4,85	0,11
ϕ1	200	6,26	0,15
ϕ1	250	7,15	0,17
ϕ1	300	6,85	0,16
ϕ1	450	10,60	0,25
ϕ1	600	10,81	**0,25**

NEGATIVE PRESSURE			
ϕ1 / ϕ2	Test Pressure (Pa)	Air Leakage (m³/h)	Air Leakage (m³/h.m)
ϕ2	50	1,70	0,04
ϕ2	100	3,33	0,08
ϕ2	150	4,43	0,10
ϕ2	200	5,55	0,13
ϕ2	250	6,75	0,16
ϕ2	300	7,44	0,18
ϕ2	450	9,83	0,23
ϕ2	600	12,15	**0,29**

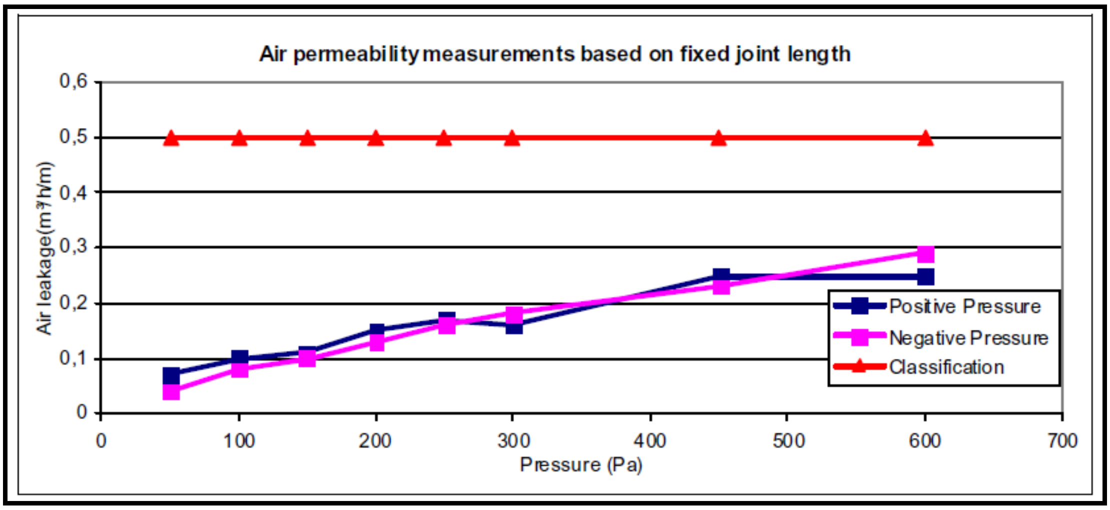


Figure 4.2. The Graph of Air Permeability Measurements Based on Fixed Joint Length

According to EN 12152 (2004), the maximum air leakage should be 0,5 m³/h.m when air permeability measurement based on the fixed joint length. In this test under 600 Pa, the result was calculated as 0,25 m³/h.m under positive air pressure; the result was measured as 0,29 m³/h.m under negative air pressure. The both results were smaller than the 0,5 m³/h.m which was maximum air leakage limit determined in TS EN 12152. Thus, the performance of the specimen accepted as successful. Herein, the value of air leakage under positive air pressure is smaller than the value of negative air pressure. So that, similar with overall area calculations, the performance of this sample was more successful in positive air pressure comparing with negative air pressure.

Through the test sequence, the static air permeability test was repeated after building movement test was conducted on the sample in order to evaluate how the performance of this sample changed after subjected to horizontal loads. Similar with the first test, the results were given in terms of based on overall area and fixed joint length, which are shown below.

Table 4.3. The Performance Table of Air Permeability Test Based on Overall Area.

POSITIVE PRESSURE			
ϕ1 / ϕ2	Test Pressure (Pa)	Air Leakage (m³/h)	Air Leakage (m³/h.m²)
ϕ1	50	3,46	0,15
ϕ1	100	3,61	0,16
ϕ1	150	4,18	0,18
ϕ1	200	4,89	0,21
ϕ1	250	5,85	0,26
ϕ1	300	7,72	0,34
ϕ1	450	8,86	0,39
ϕ1	600	11,83	**0,52**

NEGATIVE PRESSURE			
ϕ1 / ϕ2	Test Pressure (Pa)	Air Leakage (m³/h)	Air Leakage (m³/h.m²)
ϕ2	50	1,55	0,07
ϕ2	100	2,63	0,12
ϕ2	150	4,06	0,18
ϕ2	200	5,06	0,22
ϕ2	250	5,94	0,26
ϕ2	300	6,41	0,28
ϕ2	450	9,23	0,40
ϕ2	600	11,22	**0,49**

Table 4.4. The Performance Table of Air Permeability Test Based on Fixed Joint Length.

POSITIVE PRESSURE			
ϕ1 / ϕ2	Test Pressure (Pa)	Air Leakage (m^3/h)	Air Leakage ($m^3/h.m$)
ϕ1	50	3,46	0,08
ϕ1	100	3,61	0,09
ϕ1	150	4,18	0,10
ϕ1	200	4,89	0,12
ϕ1	250	5,85	0,14
ϕ1	300	7,72	0,18
ϕ1	450	8,86	0,21
ϕ1	600	11,83	0,28

NEGATIVE PRESSURE			
ϕ1 / ϕ2	Test Pressure (Pa)	Air Leakage (m^3/h)	Air Leakage ($m^3/h.m$)
ϕ2	50	1,70	0,04
ϕ2	100	3,33	0,06
ϕ2	150	4,43	0,10
ϕ2	200	5,55	0,12
ϕ2	250	6,75	0,14
ϕ2	300	7,44	0,15
ϕ2	450	9,83	0,22
ϕ2	600	12,15	0,26

The performance of the air permeability of the specimen was measured by comparison method in accordance with TS EN 13116 (2004). Herein, the results of first and second tests were analyzed. When calculation based on overall area and fixed joint length, the second test results should be within the ± 0.3 $m^3/h.m^2$ and ± 0.1 $m^3/h.m$ range of the first test results respectively. Herein, it can be said that the upper and lower limit of the range is determined as the 20% tolerance of maximum air leakage values. In other words, for overall area calculations, the maximum air leakage was specified in TS EN 12152 (2004) as ±1,5 $m^3/h.m^2$ and the 20 percent of ± 1,5 $m^3/h.m^2$ is ± 0.3 $m^3/h.m^2$. Similarly, the maximum air leakage was specified in the same norm as ±0,5 $m^3/h.m$ for fixed joint calculations and the 20 percent of ± 0,5 $m^3/h.m$ is ±0.1 $m^3/h.m$.While looking at the second test results, it is seen that the second test results were between the determined range for both overall area and fixed joint calculations. So that it can be said that the sample showed consistency in terms of air permeability performance. The comparison table, which was prepared in the light of this information, is given below.

Table 4.5. Comparison Table of First and Second Air Permeability Tests

Test	Direction	First Test	Range	Second Test	Result
Air Permeability (Overall Area $m^3/h.m^2$)	Positive	0,47	0,17 < x < 0,77	0,52	OK
	Negative	0,53	0,23< x < 0,83	0,49	
Air Permeability (Fixed Joint $m^3/h.m$)	Positive	0,25	0,15 < x < 0,35	0,28	
	Negative	0,29	0,19 < x < 0,39	0,26	

According to comparison table and graphs, it is seen that in the first test, the specimen was more successful under positive air pressure in comparison to negative air pressure for both overall area and fixed joint calculations. But after applying building movement test, the results were dramatically changed.The values taken from negative air pressure became smaller than the positive air pressure. So that, the building movement test directly affected the performance of the specimen in terms of its behavior under positive and negative air pressure.

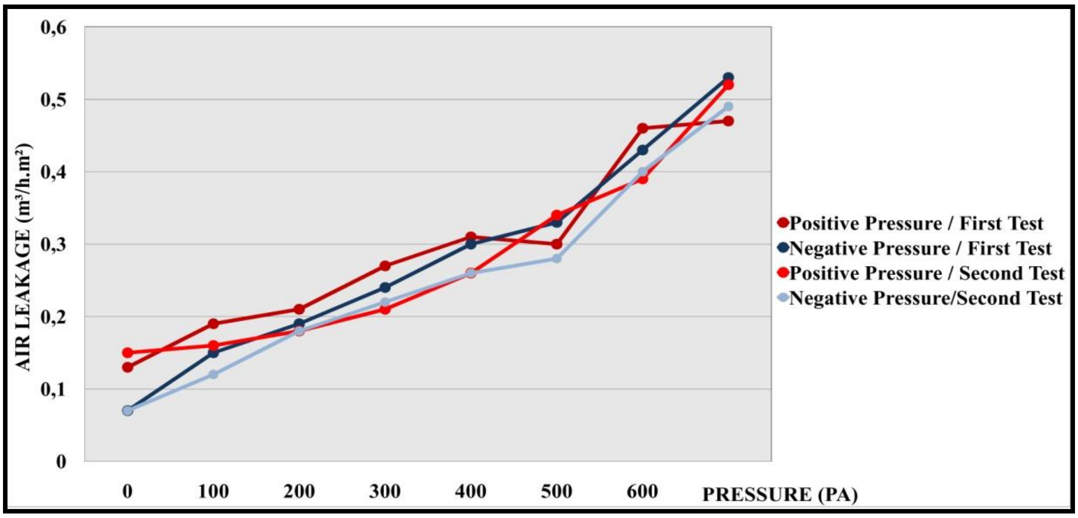


Figure 4.3. Comparison Graph of First and Second Air Permeability Tests in terms of Gross Area

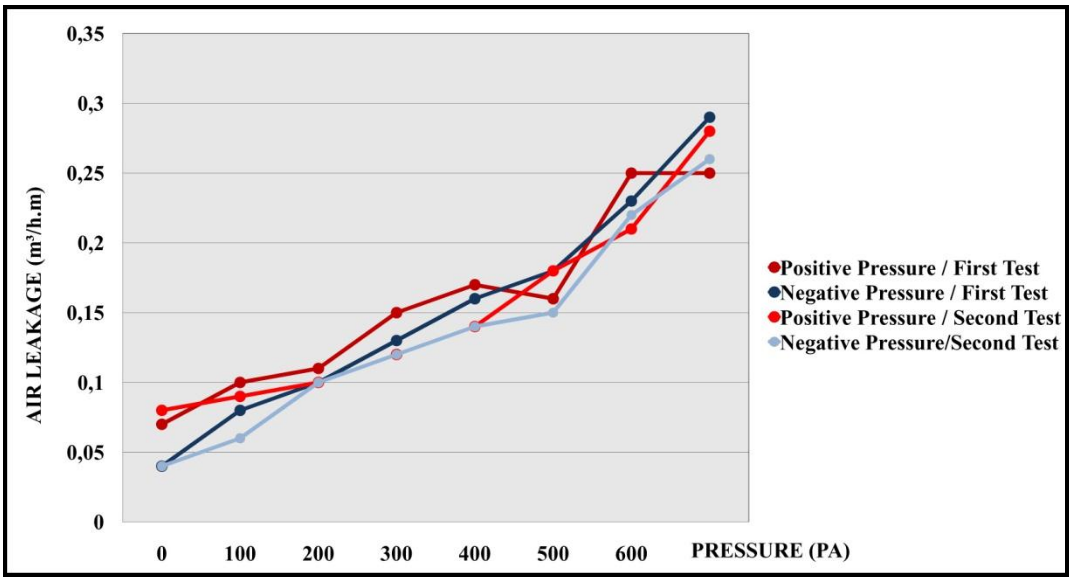


Figure 4.4. Comparison Graph of First and Second Air Permeability Tests in terms Fixed Joint Length

As a conclusion, due to the results of the air permeability tests shown in comparison graphs and the table are smaller than the maximum air leakage limit mentioned in TS EN 12152 (2004), the specimen became successful from the air permeability test and the sample was classified under A4 class toward TS EN 12152.

4.1.2 Watertightness Laboratory Test Under Static Pressure

The watertightness laboratory test under static pressure was conducted through TS EN 12154 (2004) and TS EN 12155 (2005). According to TS EN 12155, The apparatus of water penetration test, which consisted of regular placed water spray nozzles, was installed on the surface of the specimen. For this project, the apparatus was composed of five rows that includes seven nozzles for each row as specified in the same Turkish standard. The water was applied to the specimen as soon as the test began and the sample was subjected to positive test pressure during the test. In addition, a continues water line was provided via nozzles that sprayed 3,4L/m². For this project, the total amount of water applied on the surface was calculated as below:

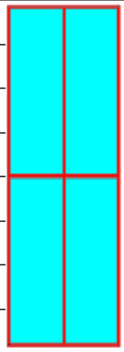
$3{,}4\ L/m^2 \times 22{,}8\ m^2 = 77{,}52\ L/min = 4651\ L/h$

Figure 4.5 The View from The Watertightness Laboratory Test Under Static Pressure
(Source: Individual Archive of The Author, 2012)

At the beginning of the test, the three pressure pulses were applied to the specimen as required by TS EN 12154 (2004). Similar to the air permeability test, 660 Pa was applied to the specimen at an interval of three seconds. The following pressure levels and their duration are shown in Table 4.6. According to this table, during the test in different pressure levels there was no water leakage observed by the test engineer on the sample so that the sample passed the static watertightness test.

Table 4.6. The Results of Watertightness Laboratory Test Under Static Pressure

Pressure Value (Pa)	Time Period (min)	Observations
0	15	No water leakage was observed.
50	5	No water leakage was observed.
100	5	No water leakage was observed.
150	5	No water leakage was observed.
200	5	No water leakage was observed.
300	5	No water leakage was observed.
450	5	No water leakage was observed.
600	5	No water leakage was observed.



In the line of the test sequence, the water penetration test was repeated after conducting second air permeability test. The method and the other conditions of the second test was totally same with the first one. At the end of the second test, there were still no water leakage seen from the curtain wall system by the test engineer. So that according to first and second test results, the specimen was accepted as successful and according to TS EN 12154 (2004), the sample was classified under R7 class.

4.1.3 Wind Resistance Test Result

The test was conducted through TS EN 13116 (2004) and TS EN 12179 (2000). Firstly, the positive test pressure was applied to the specimen. After positive test pressure was conducted, negative test pressure was implemented. For both tests, the same method was used.

The aim of wind resistance test was to define frontal displacement of vertical members under positive and negative pressure. This measurement was provided by three position sensors which were placed in a specific location on the vertical member. These position sensors were used to measure the displacements of vertical member of sample in horizontal direction under positive and negative pressure. The coordinates of sensors and the application photo are shown below in Figure 4.6 and Table 4.7.

It is significant that the frontal displacements should be smaller than L (Floor Height) mm / 200 or 15mm, whichever smaller is accepted, determined in TS EN 12179 (2000). For this project, floor height was 3800 mm. The division of 3800 to 200 mm is 19 mm which is greater than 15 mm. So that the frontal displacements of the curtain wall system should not be greater than 15 mm.

Figure 4.6. Three Position Sensors Placed on the Vertical Member

Table 4.7. The Coordinates of Three Position Sensors

	X coordinates (mm)	Y coordinates (mm)
External Dimensions	3000	3800
Sensor 3	1500	3775
Sensor 2	1500	1900
Sensor 1	1500	25

After the apparatus of the wind resistance test was prepared, it was time to conduct initial pressure levels to the specimen. These three pressure levels should be either 50% of design wind load or 500 Pa whichever is greater through TS EN 12179 (2000). In this test, the design wind load was given as 2915 Pa. So that %50 of design load is calculated as 1458 Pa for both negative and positive pressures. Thus, 1458 Pa pressure level was applied to the specimen for three times at the interval of three seconds. Thereafter, the curtain wall specimen was subjected to the test pressure in four stages, for a minimum period of 15s ± 5s at each stage up to design wind load, i.e 25%, 50%, 75% and 100% of design wind load. After test pressures were applied tor the specimen, the result was calculated through the values taken from the sensors. Herein, it was seen that the values taken from second sensor was greater than the other both sensors. Because the first and third sensors were located on the anchorage point of the curtain wall system whereas there was not any anchorage point on the second sensor. Then, the frontal deflection was calculated according to this formula mentioned in TS EN 12179 (2000):

$$\text{Frontal Deflection} = \text{Point 2} - \left(\frac{\text{Point 1} + \text{Point 3}}{2}\right)$$

According to results table, it is seen that the frontal deflections in both negative and positive test pressure, which were 7,91 mm for positive pressure and 6,67 mm for negative pressure, were smaller than maximum frontal deflection. As mentioned before, for this project maximum deflection was calculated as 15 mm through TS EN 12179 (2000). So that these results indicated that the performance of the specimen was successful in terms of wind resistance. Accordingly, the applied positive and negative pressure levels, the frontal displacements are shown below.

Table 4.8. Frontal Deflections on The Vertical Mullion

Positive Pressure (Pa)	Point 1 (mm)	Point 2 (mm)	Point 3 (mm)	Frontal Deflection (mm)
0	0,00	0,00	0,00	0,00
729	0,70	2,19	0,34	1,67
1458	1,48	4,89	0,91	3,70
2187	2,50	7,79	1,55	5,77
2915	3,64	10,81	2,17	7,91
0	0,5	0,7	0,16	0,37

Negative Pressure (Pa)	Point 1 (mm)	Point 2 (mm)	Point 3 (mm)	Frontal Deflection (mm)
0	0,00	0,00	0,00	0,00
-729	0,87	2,36	0,87	1,49
-1458	1,60	4,80	1,64	3,18
-2187	2,30	7,11	2,46	4,73
-2915	3,28	10,51	4,39	6,67
0	0,30	1,12	1,56	0,19

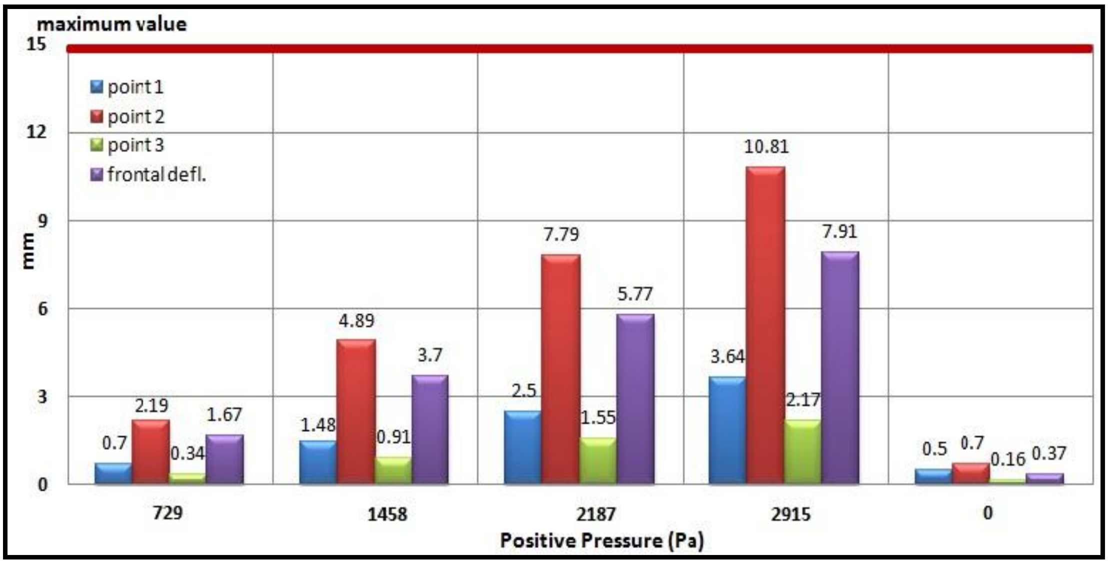


Figure 4.7. Displacement and Frontal Deflection of The Specimen Under Positive Pressure

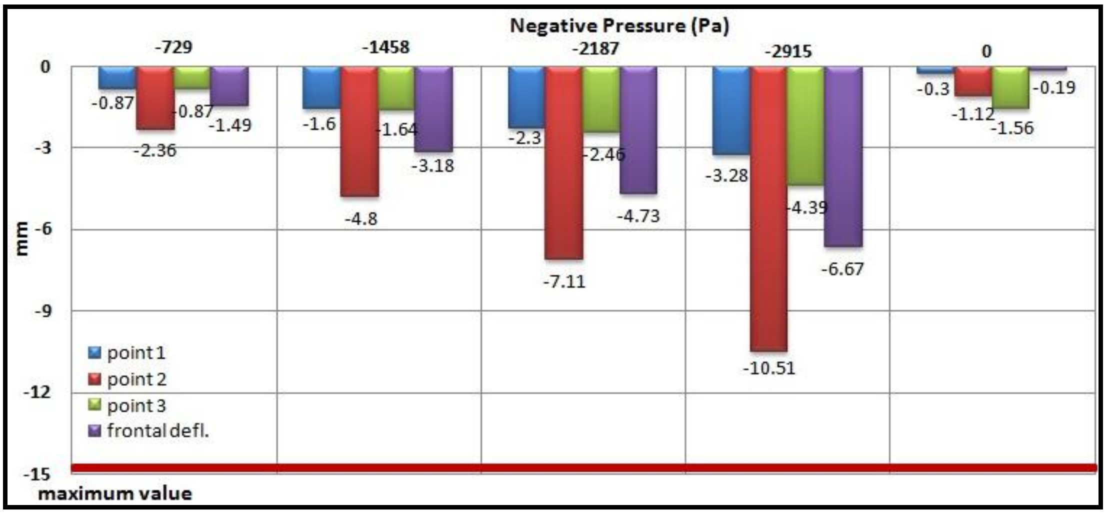


Figure 4.8. Displacement and Frontal Deflection of The Specimen Under Negative Pressure

4.1.4 Building Movement Test Result

In this study, static building movement test was applied to the panel curtain wall sample in accordance with AAMA 501.4 (2009). According to this norm, the upper and bottom horizontal members of the specimen were fixed to the stable steel beam of the test apparatus and the middle horizontal member of the specimen was anchored to the moveable steel beam of the test apparatus. Then the moveable steel beam was directed in the horizontal direction. This test consisted of three full cycles. Herein, a cycle was defined as a full displacement in one direction then back to originating point, full displacement in the opposite direction and finally back to the originating point. The design displacement was determined by formula through AAMA 501.4 (2009) given below:

Design displacement (mm) = 0.010 x the greater of the adjacent story height (mm)

In this project, the story height was 3800 mm. Through related formula mentioned above, the sample was directed in horizontal direction toward X coordinate up to ± 38 mm. During the test, test engineer observed the sample in order to evaluate how the sample behaved under horizontal loads. At the end of the test, there was no damage observed in the panel curtain wall specimen in other words there were not any glass breakage, separation on the fittings, distortions at the corners or other damages. Herein, especially the glass fall out is significant concern under seismic load especially for high-rise buildings. In addition, during an earthquake glass breakage are very dangerous for surrounding environment of the building. In this project , it can be said that this sample can perform successful behavior if the curtain wall expose to horizontal loads because there were not any damages observed on the curtain wall under 19 mm displacement in x direction.

Within this framework, through a personal interview, Murat Seyhan who is the general manager of the Facade Testing Institute quote,

> *"Building movement tests are demanded by the system developers or the contractors for panel curtain wall systems. These buildings are generally high-rise buildings or special projects. But there is not any conducted building movement test on other types of the curtain wall systems which are constructed with stick construction technique in this test center. The reason may be sourced from the knowledge about the stick construction technique in terms of its installation method to the building. In this technique the vertical members are fixed to the building, which may not succeed tolerating the horizontal loads such as wind and seismic."*

4.2 Facade Performance Tests and Their Improvements

In recent years, the performance facade tests become preferable applications especially for large-scale and qualified projects demanded by the project owner and the architect from the building contractor. Herein, it is expected from the aluminium system to satisfy the required criteria for taking the certificate of achievement from specified curtain wall tests. The types of facade tests for applying the building envelope is determined by the architect and the investor of the project. In this investigation, for analyzing the performance of a unitized aluminium curtain wall system, the facade tests were used with the demand of the project owner. It was expected that the panel system of this tower succeeds the air permeability, watertightness, wind resistance and static building movement tests through relevant standards. As mentioned in the results of applied facade tests subheading, the sample satisfied the requirements determined in related norms and became successful from conducted tests. But within this period, it was observed that there were some problems in facade tests in terms of their application methods and details. According to critical approach on curtain wall tests, the specified problems are listed below:

- In the test laboratory, the real weather and site conditions are intended to be achieved as much as possible with building construction site whereas it could not be totally same. The sample may not reflect the real-life performance in a laboratory environment. At this point, the site tests shall be applied to the sample after laboratory tests are implemented. In this way, after mock-up successfully passes the tests in a laboratory, the nearest conclusions in terms of the real-life performances of these samples can be obtained. However today in-situ tests are limited to water and air tests, the other test types are not applied to the sample yet.

- This study indicates that the similar glass combinations are used in curtain wall systems in qualified projects. In these projects the glazing part mostly consists of low-e coating, laminated or tempered glasses. But it was seen in this study that the effects of different combinations of glasses were ignored in terms of its impact on the total performance of the curtain wall system in facade tests. Moreover, the performance of the glazing part could not be evaluated individually because conducted curtain wall tests indicated the total performance of the system. As a result, these facade tests are suitable for analyzing the total performance of the curtain wall system whereas these tests are not appropriate for the evaluation of the components of the systems such as glazing part, aluminium frames etc. separately.

- In static and dynamic building movement test, it was seen in this study that there is not any equivalent value of the applied load to the specimen in terms of the Richter scale. This fact does not reflect the real life conditions of the building in terms of seismic behavior. Moreover, the specimen is moved only in x and y direction. But during an earthquake, the building vibrates and it is exposed to ground shaking. In other words, the building does not direct only in x and y direction.

- In water tightness and the building movement tests, the performance of the specimen is evaluated only by observation. The test engineer detects the glass breakage, separation on the fittings, distortions at the corners or other damages by means of visual assessment. There is not any obtained data from the computers in this test method.

- In wind resistance performance of the curtain wall, it was observed that there are not any separate calculation for the bottom and the top parts of the curtain wall system. But in reality, the wind speed increases with the building height. In other words, the wind speed is stronger at the upper part of the building. So that the wind performance calculations should be measured separately for the bottom and upper part of the building. In addition, for super tall buildings, the building facade may divide into many parts and the wind speed may be calculated for each level. Thus, more accurate curtain wall design can be obtained. When looking at the wind resistance facade test, it was seen that the calculations are based on the maximum floor height. In other words in order to be on the safe side, the curtain wall system is completely designed through the critical part of the building. But this condition may be accepted as overdesign in terms of wind factor.

4.3 Benefits of Panel Construction Technique In Comparison To Stick Construction Technique

In this investigation, in addition to the performance report of panel curtain wall system, the performance report of the conventional curtain wall system belongs to one of the residential building was gathered from facade testing company in order to compare the results in between. It is aimed to analyze how panel and conventional systems behave in the same conducted tests. The dimension of this sample was 4000 mm to 4894 mm. The glass combination of the mock-up was defined as (5mm + 1,52 PVB + 5 mm) +16mm Air Gap + 8 mm insulated glass. According to performance results which is given in Figure 4.9, the specimen belongs to conventional curtain wall system also satisfied the watertightness, air permeability and wind resistance tests with respect to required standards. In addition it is seen that there is not so much difference in these applied curtain wall tests between both panel and conventional system. Related to this comparison the test engineer Öner Arslan who has been attended to both facade tests stated that the specimen either belongs to a panel or conventional curtain wall systems mostly become successful from the watertightness and air permeability performance tests similar within this study. But it was mentioned that the determinant test for demonstrating the differences between the unitized system and the conventional system is building movement test. Throughout this study, it is seen that the building movement test has applied to the only unitized type of the curtain wall system; there is not any conducted movement test for other types of curtain wall systems which are constructed with stick construction technique. Even this situation is also adequate to understand that the panel curtain wall system by means of acting as a flexible skin become more successful against horizontal loads. But the other systems constructed with stick construction technique may not provide sufficient success because the frames of this system are fixed to the building which may exert the curtain wall system while tolerating the horizontal loads such as wind and seismic movement as mentioned before. The reason for no demand on the other systems instead of panel curtain wall system may be sourced from the knowledge about the deficiency installation of the stick construction technique.

	CONDITIONS	RESULTS		CLASSIFICATION
AIR PERMEABILITY EN 12152	at 600 Pa ϕ < 1,5 m³/h,m²	Positive Pressure	0,35	A4
	at 600 Pa ϕ < 0,5 m³/h,m		0,15	
	at 600 Pa ϕ < 1,5 m³/h,m²	Negative Pressure	0,98	A4
	at 600 Pa ϕ < 0,5 m³/h,m		0,15	
WATER-TIGHTNESS (Static Pressure) EN 12154	There will be no water leakage at 600 Pa	No water leakage was observed at 600 Pa.		R7
RESISTANCE TO WIND LOAD EN 13116	Deflection < 13,33 mm at 1000 Pa	OK (max. 2,56 mm) (max. -2,33 mm)		OK
	There will be no damage at secure load	No damage was observed.		

Figure 4.9. The Performance Test Report of Conventional Curtain Wall System

Throughout this study, the disadvantages of the stick construction technique has been mentioned. As mentioned before, there are two main aluminium curtain wall systems in terms of conventional and structural glazing curtain wall system installed to the building with stick (frame) construction technique. But the panel curtain wall is the only system constructed with panel construction technique. In the light of applied facade tests and conducted interviews, it is seen that the panel construction technique, which is carried and applied in modular form, provides some advantages comparing the stick construction technique, which are listed below:

- In contradistinction to stick construction technique, panel construction technique allows maximizing factory labor. In addition, this technique minimizes site labor, which decreases the potential of faults caused by workers in the construction stage. This fact results in improved quality control during fabrication and construction stages. Herein, especially for high-rise buildings, there should not be almost any deviation of the anchor points at the curtain wall. Otherwise, the faults in application details turn into a big problem when the height of the facade becomes taller. With the pre-defined anchor points, the risk is less than stick construction technique. Moreover, the installation can be applied easier and the construction period getting shorter via prefabricated modules of the system. This is a preferable condition for architects especially for high-rise buildings to construct the facade by using this system owing to many time saving for construction and installation stages. It is certain that in building construction, minimum time means maximum cost efficiency.

- Without the need of scaffold in building construction, the safety of the workers is at the highest level in panel construction technique. But in stick construction, using scaffold is obligatory for the erection of the curtain wall. In addition, a minimum number of workers are needed in panel construction technique, which provides cost efficiency for the contractors.

- In panel construction technique, the installation of prefabricated modules can be applied from both interior and exterior of the building, which provides flexibility for the erection of the curtain wall system. But in stick construction technique, the installation of the glass to the pre-installed vertical members can be done only from the outside of the building.

- The panel curtain wall technique provides advantages in terms of maintenance of the curtain wall system. When the scale of the building facade increase, the maintenance concern become more noteworthy. Due to its modular form, unitized system provides facilities for changing distorted or broken part of the system. Although if there is any problem occurs in the stick construction technique, the compensation of the problems is very difficult comparing to panel construction.

As mentioned above, panel construction technique provides many facilities comparing to stick construction technique. Similarly, due to constructed with this technique, panel curtain wall system posses the same advantages. But the literature survey indicates that the higher shipping costs and the necessity for sequential installation are the disadvantages of this system comparing to stick system. In panel construction technique, one module interlocks with the next, so the modules must be installed in a particular sequence; whereas stick construction technique permits more freedom. In addition, the main disadvantage of the system is that the square meter price of unitized system is still expensive when compared with conventional and structural glazing curtain wall systems in Turkey.

CHAPTER 5

CONCLUSIONS

The current architectural approach is designing extensive surface glass applications, which leads to a new aesthetic trend directly affecting the city silhouette. Not only tall buildings but also low rise offices, commercial or residential buildings have been enveloped by means of large amounts of glasses and metal combinations instead of stone, wood or other traditional materials. Due to providing design flexibility, better tolerance, durability and the eco-friendly attitude, aluminium has become the material of choice for building facade. In this investigation, aluminum curtain wall systems were reclassified according to recent developments, and the main design principles in terms of architectural and constructional of these systems were determined. In addition, the performance criteria of curtain wall systems were described in terms of environmental and human sourced factors and the recent innovations in the glazing systems integrated into the building envelope were pointed out.

At curtain wall sector, it is aimed to minimize the shortcomings of the latest improved products and find out new solutions for increasing their performance in a similar way to other fields in the building construction sector. Herein, the panel curtain wall system, which is constructed with panel construction technique, is determined as the modern and the innovative aluminium curtain wall system. Furthermore, as exemplified in Appendix B, in the recent and prestigious projects, the demand of the architects and the contractors begins to replace with panel curtain wall system instead of the conventional curtain wall system which is constructed with stick construction technique. Accordingly, there are some problems known related to stick construction technique in terms of its behavior against horizontal loads, the duration of installation phase, compulsory use of scaffolds in the erection of the system and the maintenance concern. Through the main aim of this study, it was pointed out why the panel curtain wall system comes to the forefront especially for high-rise buildings and the pros and the cons of this system were investigated. In addition, it was analyzed how this system behaves against the problems seen in the stick construction technique.

According to the method of this study, the performance of unitized system was measured by conducting facade tests. These curtain wall tests are prominence applications demanded by project owners and architects in order to evaluate the success of the cladding system. In this study, a full scale mock-up which belongs to one of the prestigious towers in İstanbul was used for conducting air permeability, water tightness, wind resistance and building movement tests. In accordance with test results, the specimen satisfied the requirements which were determined according to related standards, explained in the result and discussion part of this study. Thus, the sample of panel curtain wall system became successful from applied performance tests.

But throughout this study, it was observed that there were some problems in facade tests in terms of general application methods and details. These were general problems affecting the whole facade tests and the specific problems related with test types. The first problem was related with the preciseness of results taken from the test laboratory because in the test laboratory, the real weather and site conditions were intended to be achieved as much as possible with building construction site whereas it could not be totally same.The specimen may not reflect the real-life performance in this environment. It was recommended that the laboratory tests shall be supported by in-situ tests in order to achieve better results. The second problem was about the evaluating of system components. It was seen in this study that the effects of different combinations of glasses were ignored in terms of its impact on the total performance of the curtain wall system. So that these facade tests are accepted as suitable for analyzing the total performance of the curtain wall system whereas these tests are not appropriate for the evaluation of the components of the systems such as glazing part, aluminium frames etc. separately.

The other determined problems were about the building movement, watertightness and wind resistance tests. In static and dynamic building movement test, there was not any equivalent value of the applied load to the specimen in terms of the Richter scale. This fact does not reflect the real life conditions of the building in terms of seismic behavior. Moreover, the specimen is moved only in x and y direction, which does not reflect the real earthquake condition because during an earthquake the building is exposed to ground shaking in other words it does not direct only in x and y direction. Furthermore, in water tightness and the building movement tests, the performance of the specimen was evaluated only by observation; there was not any obtained data from the computers in these test methods. Lastly, in the wind resistance performance of the curtain wall, it was observed that there are not any separate calculation for the bottom and the top parts of the curtain wall system. But in reality, the wind speed increases with the building height so that the calculations should be done separately for each bottom and the top part of the building in wind resistance test.

In this investigation, in addition to the performance report of panel curtain wall system, the performance report of the conventional curtain wall system belongs to one of the residential building was gathered from facade testing company in order to compare the results in between. It is aimed to analyze how panel and conventional systems behave in the same conducted tests. According to performance results, the specimen belongs to conventional curtain wall system also satisfied the watertightness, air permeability and wind resistance tests with respect to required standards. In addition it is seen that there is not so much difference in these applied curtain wall tests between both panel and conventional system. But it is seen that the determinant test for demonstrating the differences between the unitized system and the other systems constructed with stick construction technique is building movement test. Throughout this study, it is seen that the building movement test has applied to the only unitized type of the curtain wall system; there is not any conducted movement test for other types of curtain wall systems constructed with stick construction technique. Even this situation is also adequate to understand that the panel curtain wall system by means of acting as a flexible skin can become more successful against horizontal loads.

According to the goal of this investigation, there were some advantages determined related to the panel construction technique in comparison to stick construction technique. Firstly, in contradistinction to stick construction technique, panel construction technique allows maximizing factory labor. In addition, this technique minimizes site labor, which decreases the potential of faults caused by workers in the construction stage. Moreover, the installation can be applied easier and the construction period getting shorter via prefabricated modules of the system. Without the need of scaffold in building construction, the safety of the workers is at the highest level in panel construction technique. But in stick construction, using scaffold is obligatory for the erection of the curtain wall. In addition, a minimum number of workers are needed in panel construction technique and the installation of prefabricated modules can be applied from both interior and exterior of the building, which provides flexibility for the erection of the curtain wall system. But in stick construction technique, the installation of the glass to the pre-installed vertical members can be done only from the outside of the building. Furthermore, due to its modular form, unitized system provides facilities for changing distorted or broken part of the system. Although if there is any problem occurs in the stick construction technique, the compensation of the problems is very difficult comparing to panel construction technique.

As mentioned above, panel construction technique provides many facilities comparing to stick construction technique. Similarly, due to constructed with this technique, panel curtain wall system posses the same advantages. Throughout this study, it can be concluded that panel curtain wall system is the preferable choice as a curtain wall system in high-rise building applications, but for low-rise buildings, unfortunately, this system is still expensive. It is expected that with the advances in technology, panel curtain wall system will become cheaper and accessible for all types of buildings.

REFERENCES

Alpur,İ.,Cam Giydirme Cephe Sistemlerinin Bilşenler Yönünden Karşılaştırılması, (p.8), A Master's Thesis, İstanbul Technical University, İstanbul, 2009.

Aluminum Curtain Wall Design Guide Manual, AAMA (American Architectural Manufacturers Association), Retrieved Jun. 19, 2012, http://www.aamanet.org

AAMA 501.4, Recommended Static Testing Method for Evaluating Curtain Wall and Storefront Systems Subjected to Seismic and Wind Induced Interstory Drift, American Architectural Manufacturers Association, 2009.

AAMA 501.6, Recommended Dynamic Test Method for Determining the Seismic Drift Causing Glass Fallout from a Wall System, American Architectural Manufacturers Association, 2009.

Alumil Curtain Wall Catalog, 2011, Retrieved Sept. 27, 2012, http://www.alumil.com.tr

Aluminium Design, Retrieved Sept. 23, 2012, http://www.aluminiumdesign.net

Alutech Sytem, Retrieved Sept. 29, 2012, http://www.alutech.com.tr/

American Architectural Manufacturers Association, AAMA 501.4,501.6,501.2-03,2012

Arnold,C., Seismic Safety of the Building Envelope, 2009, http://www.wbdg.org/resources/env_seismicsafety.php

Atalay,B., Alüminyum Giydirme Cephe Sistem Seçiminde Uygulama Öncesi Süreç Analizi, (p.13). A Master's Thesis, Istanbul Technical University, Istanbul, 2006.

Bayram,A., Energy Performance of Double Skin Facades in intelligent Office buildings:A Case Study In Germany, (p.31), A Master's Thesis, Middle East Technical University, Ankara, 2003.

BBRI, Ventilated Double Facades, Department Of Building Physics, İndoor Climate & Building Service, Belgian Building Research Institute, Belgium, 2004

BCI (Architectural Glazing and Building Enclosures Company), USA, Retrieved Sept. 30, 2012, www.bcindustries.com

Begeç H. and Savaşır K., Akıllı Giydirme Cephe Sistemlerinin Havalandırma Şekillerinin İncelenmesi, Paper, Roof and Facade Expo, CNR, İstanbul, April 2-3, 2004.

Beijing Jangho Curtain Wall Company, Retrieved Dec.13, 2012, www.janghogroup.com

Brookes, A., Cladding of Buildings, (p.191)., Spon Press, London, 1998

Büyükkılıç,S.G., An Appraisal of Structural Glass Wall Systems With Emphasis On Spider Fitting Details, (p.13). A Master's Thesis, Middle East Technical University, Ankara, 2003.

Centre for Window and Cladding Technology, Technical Note 64, Oct,2008, http://www.cwct.co.uk/

Clausen,L.M., Belluschi and the Equitable Building in History, (p.109-129), Journal of the Society of Architectural Historians, Vol. 50, No. 2, University of California Press, Chicago, Jun., 1991. Retrieved Aug. 17, 2012, http://www.jstor.org/stable/990589

Construction Week, Retrieved Dec. 14, 2012, www.constructionweekonline.com

Council for Aluminium in Buildings (CAB), Retrieved Sept. 28, 2012, http://www.c-a-b.org.uk

CWG (Engineering and Consultancy Services), Istanbul, Retrieved Sept. 25, 2012, http://www.cwgweb.net

Çakmanus, İ. and Türkoğlu, H., Ankara'daki Mevcut Bir Ofis Binasında Doğal Havalandırmanın Uygulanabilirliğinin İncelenmesi, Paper, VI. International Mechanical Installation Symposium,İstanbul, May.,2004

Doğruel,N., Binalarda Cephe Kaplamalarının Isı Yalıtımına Etkisi, (p.25-26), A Master's Thesis, Trakya University, Edirne, 2010.

Dupont, Retrieved Sept. 20, 2012, http://tyvek.com.tr/Tyvek

Facade Testing Institute, Nov.13, 2012, http://fti-europe.com

Garg, N.K., Guidelines for Use of Glass in Buildings, (p.119), New Age International, Delhi, IND , 2007, Retrieved Aug. 22, 2012, http://site.ebrary.com/id/10318669?ppg=119

Güvenli,Ö., Tarihsel Süreç İçinde Malzeme Cephe İlişkisi ve Giydirme Cepheler, (p.45)., A Master's Thesis, Yıldız Technical University, İstanbul, 2006.

Harrison, K., & Meyer-Boake, T. The Tectonics of the Environmental Skin, University of Waterloo, School of Architecture, Canada, 2003. http://www.fes.uwaterloo.ca/architecture/faculty _projects/terri/ds/double.pdf

Hürriyet, Retrieved Dec. 12, 2012, www.hurriyet.com.tr

Istanbul Metropolitan Municipality Department of Fire Report, 2012

Kılıç,A., Cephe Kaplamaları ve Cephe Yangın Güvenliği, Conference Paper, YEM, Sept 16, 2012, Istanbul

Krynski,M., Dynamic response of architectural glazing subject to blast loading, (p.35), A Master's Thesis, University of Toronto, Canada, 2008

Metal Yapı, Retrieved Sept. 15, 2012, http://www.metalyapi.com/

National Glass, Retrieved Sept. 30, 2012, http://www.nationalglass.com

Next Level Project, Retrieved Dec. 13, 2012, www.nextlevel.com

OMA Architects, Retrieved Dec. 13, 2012, http://oma.eu

Patterson,M.R., Structural Glass Facades: A unique Building Technology, (p.25-26)., A Master's Thesis, University of Southern California, San Francisco, 2008.

Poirazis, H , Double Skin Facades: A Literature Review, (p. 66-68), Lund Institute of Technology, Lund University, 2004
http://www.ebd.lth.se/fileadmin/energi_byggnadsdesign/images/Publikationer/Bok-EBD-R3-G5_alt_2_Harris.pdf

RMJM Architects, Retrieved Dec. 13, 2012, www.rmjm.com

Sanders,M.R., CurtainWalls: Not Just Another Pretty Facade, Hofmann Architects Journal, Issue: 1, Vol:23, AIA, 2006

Sev,A., 2009, Sürdürülebilir Mimarlık, (p.104), Yem Publication, İstanbul, 2009, (ISBN:978-9944-757-22-5)

Schenider,J., Making Visions Reality, Engineered Transparency: The Technical, Visual, and Spatial Effects of Glass,(p.184), Princeton Architectural Press,Newyork,2008, http://site.ebrary.com

Schueco, Retrieved Sept. 29, 2012, http://www.schueco.com

Schwartz, T.A., Curtain Walls, (p. 37-45), APT Bulletin,Vol. 32, No. 1, Association for Preservation Technology International (APT), 2001

Scott, M., Contemporary Curtain Wall Architecture, (p.7,68,69), Princeton Architectural Press, Newyork, 2009, http://site.ebrary.com/id/10482151?ppg=68

Skyscapercity, Retrieved Dec. 13, 2012, www.skyscapercity.com

Society of Fire Protection Engineers, Guidelines for Designing Fire Safety in Very Tall Buildings Public Review Draft March, 2012
http://www.sfpe.org

SOM Architects, Retrieved Dec. 13, 2012, www.som.com

Şenkal,F., Giydirme Cephe Sistemlerinin Üretim ve Uygulama Aşamalarının İncelenmesi, Paper, Roof and Facade Expo, CNR, İstanbul, March 25-26, 2005.

Tekin Ç. “Giydirme Cephe Sistemlerinde Test Metodları” Paper, Roof and Facade Expo, İstanbul, 2006.

The Report of Enclos Corp’s Advanced Technology Studio (ATS), Insight Magazine, (p. 28), June 2010, http://www.enclos.com

Tığ G.,İrtem E., 3. International Materials and Technologies Symposium on Roof and Wall Cladding,Conference Paper, I.T.U, Istanbul ,Sept. 17-18, 2006.

Trakyacam, The Company Presentation, Ministry of Environment and Urban Planning, Ankara,2012.

Tortu,Ş.Ş., Alüminyum Giydirme Cephelerde Isıl Performans Durabilite İlişkisinin İncelenmesi, (p.3)., A Master’s Thesis, İstanbul Technical University, İstanbul, 2006.

Turkey’s Regulation on Fire Protection, 2010

TS EN 12152, Curtain walling -Air permeability- Performance Requirements and Classification, Turkish Standards Institution, December, 2004

TS EN 12153, Curtain walling -Air permeability- Test method, Turkish Standards Institution, November, 2006.

TS EN 12154, Curtain walling - Watertightness - Performance Requirements and Classification, Turkish Standards Institution, April, 2005.

TS EN 12155, Curtain walling - Watertightness - Laboratory Test Under Static Pressure, Turkish Standards Institution, March, 2005.

TS EN 12179, Curtain walling -Resistance to Wind Load- Test Method, Turkish Standards Institution, June, 2000.

TS EN 13830, Curtain walling - Product standard, Turkish Standards Institution, March, 2005.

Winxie,W.W.S., Analysis and Design of Curtain Wall Systems for High Rise Buildings, (p.25-26), University of Southern Queensland, Australia, 2007.

Yeomans, D., The Origins of the Modern Curtain Wall, APT Bulletin , (p. 13-18)., Vol. 32, No.1, Curtain Walls, Association for Preservation Technology International (APT), 2001.
Retrieved Jun. 17, 2012, http://www.jstor.org/stable/150468

APPENDIX A

TYPICAL ALUMINIUM PANEL CURTAIN WALL DETAILS

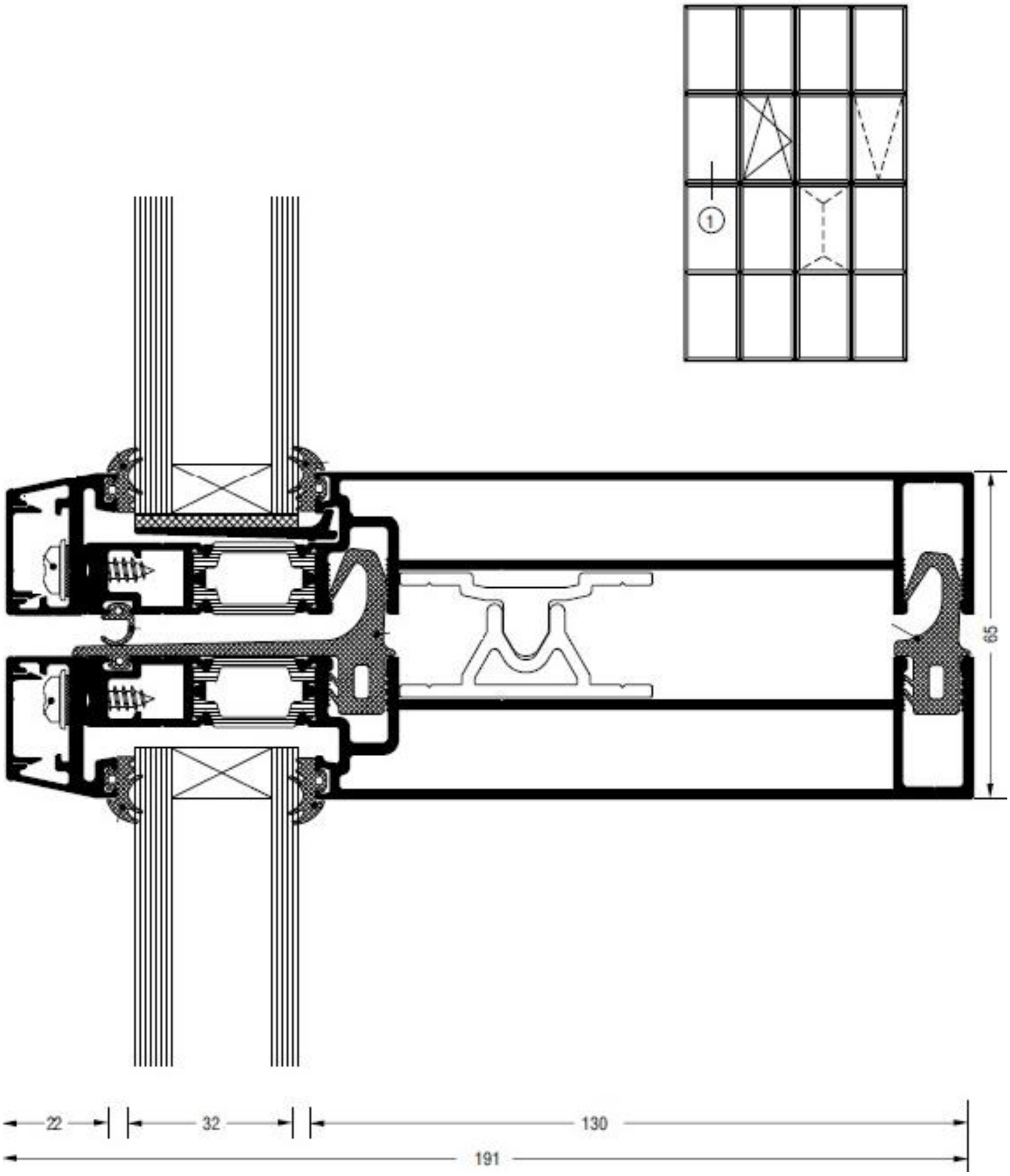


Figure A.1 The Detail of Horizontal Member At The Connection of Two Modules
(Source: Alumil Curtain Wall Catalog, 2011)

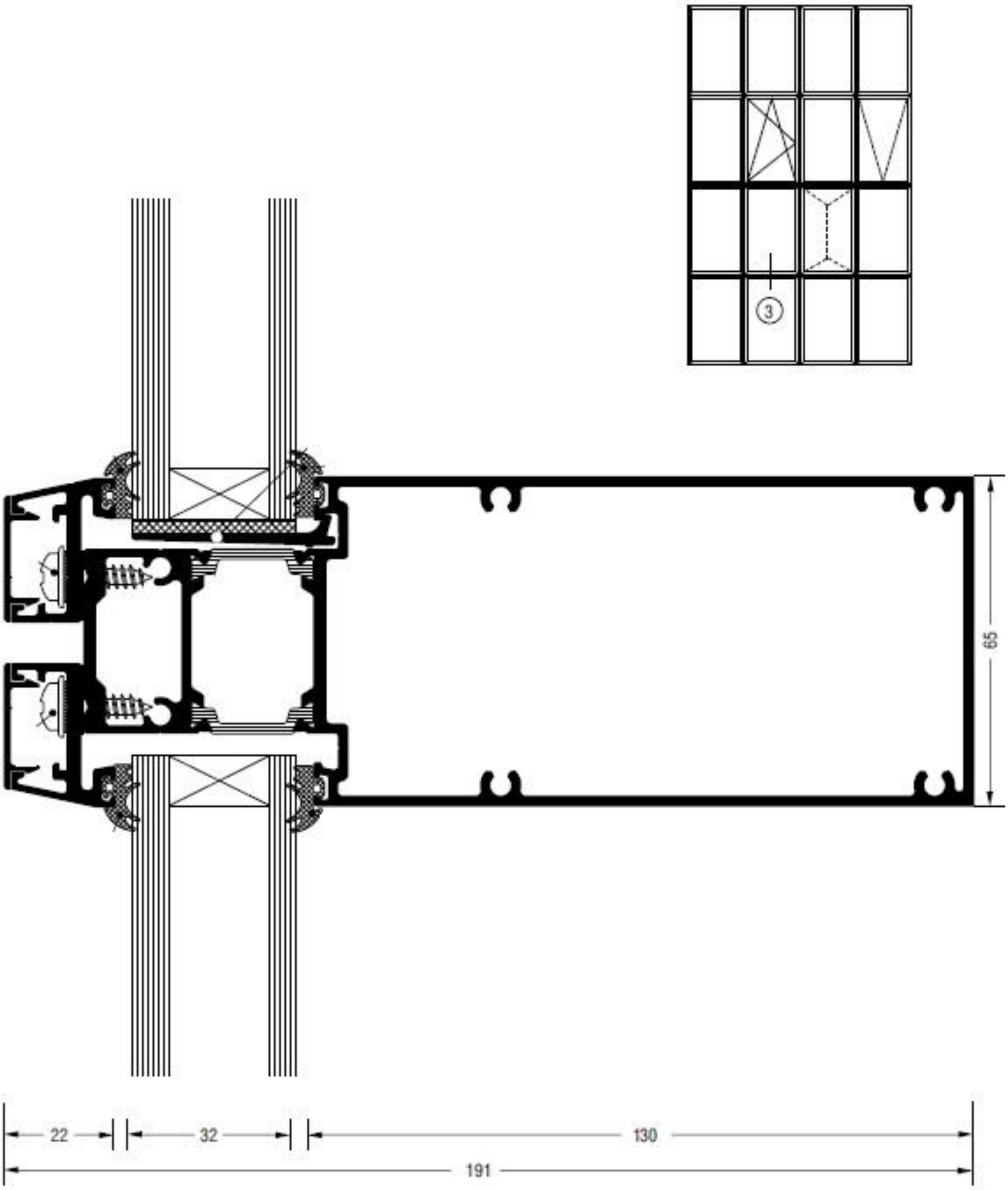


Figure A.2. The Detail of Horizontal Member In The Mıddle of The Module
(Source: Alumil Curtain Wall Catalog, 2011)

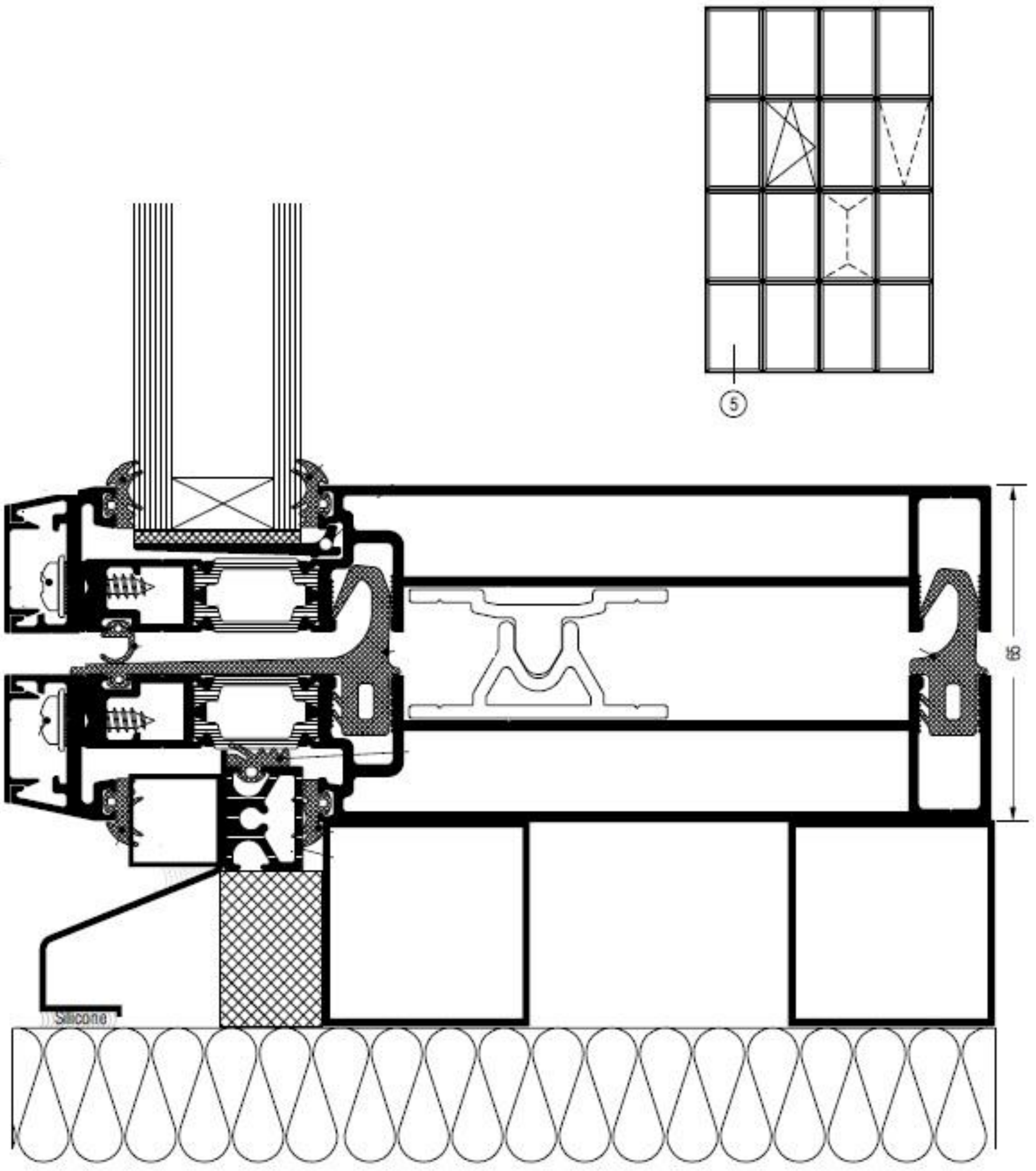


Figure A.3. The Detail of Horizontal Member At The Ground Connection
(Source: Alumil Curtain Wall Catalog, 2011)

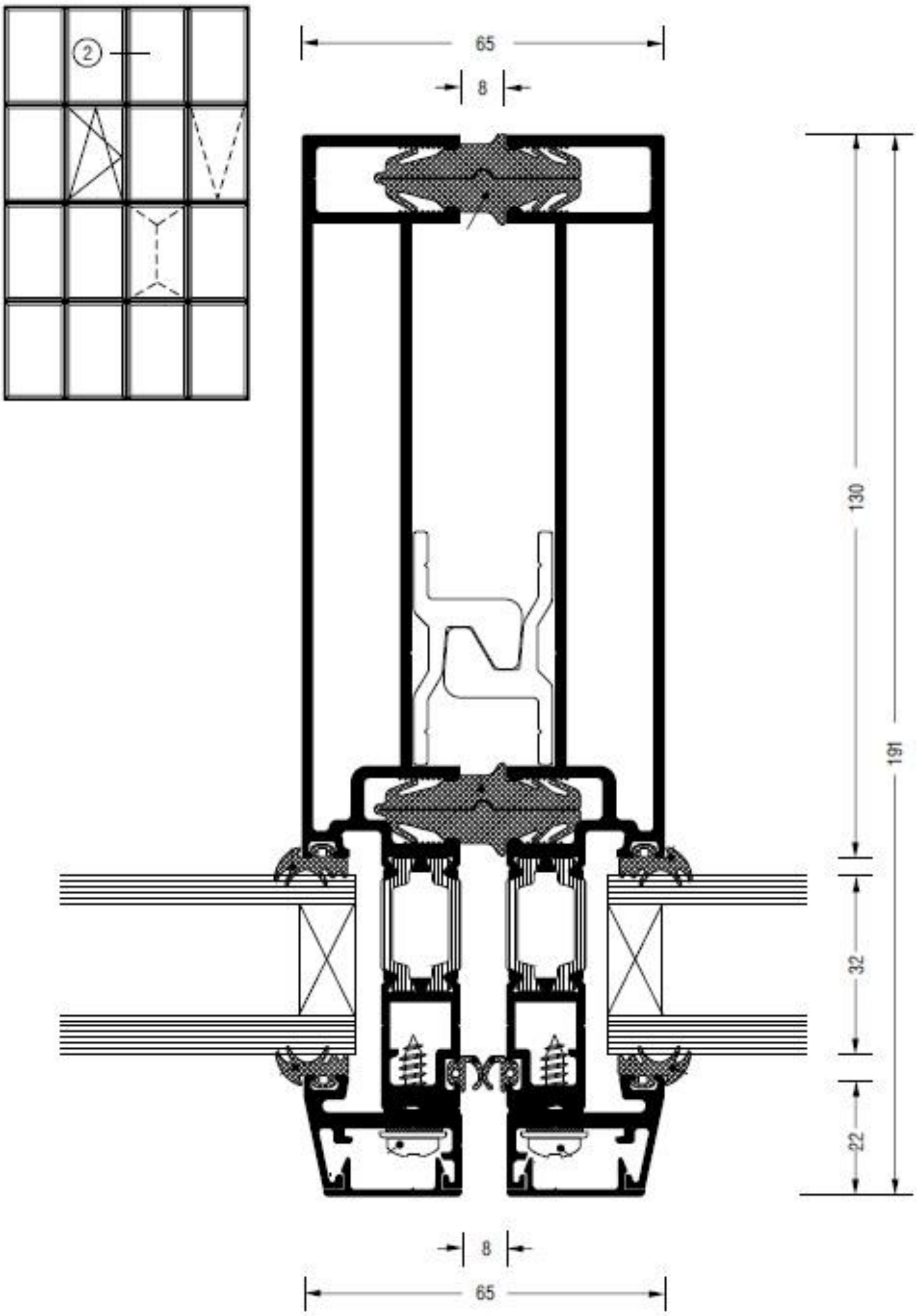


Figure A.4 The Detail of Vertical Member At The Connection of Two Modules
(Source: Alumil Curtain Wall Catalog, 2011)

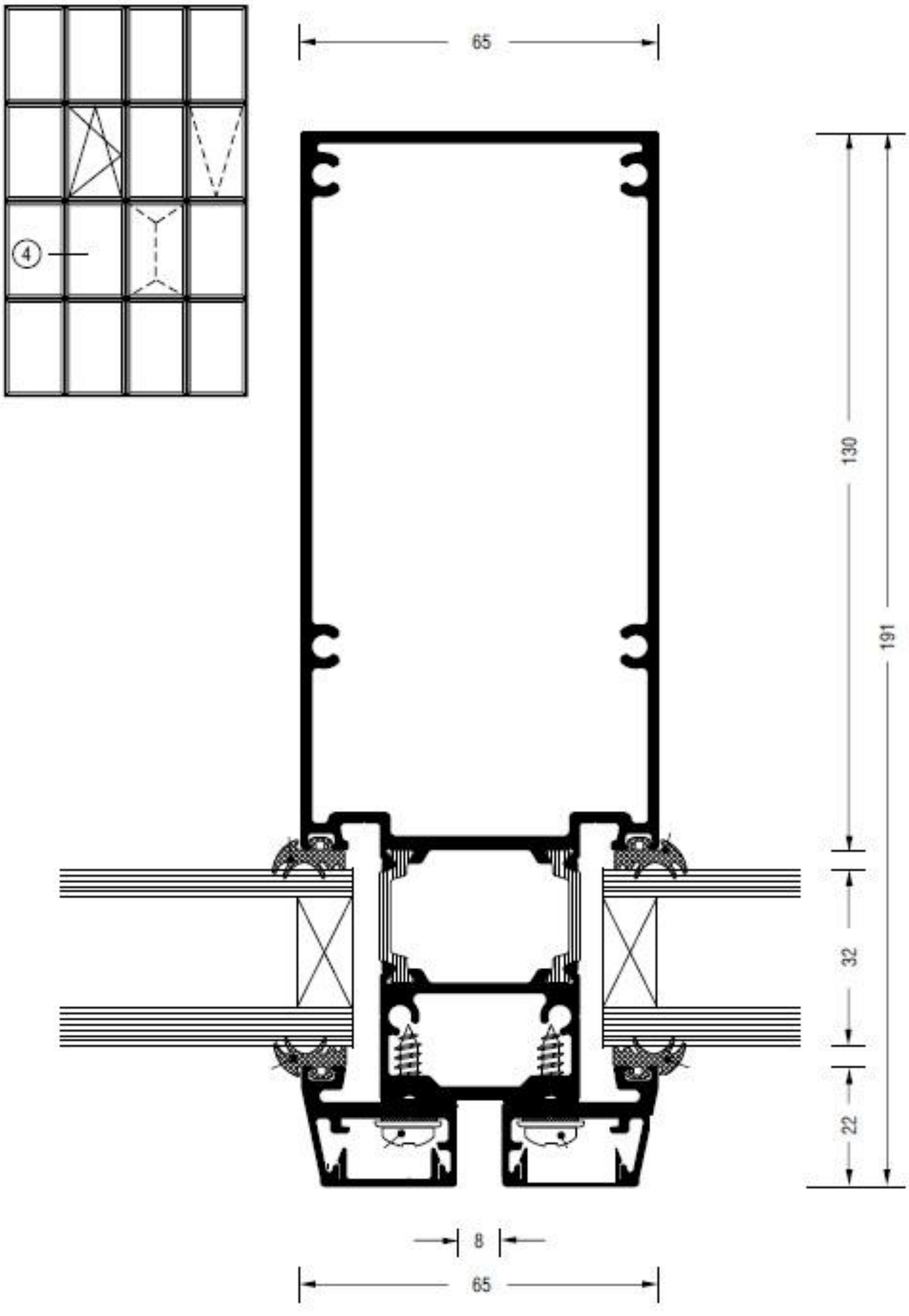


Figure A.5. The Detail of Vertical Member In The Mıddle of The Module
(Source: Alumil Curtain Wall Catalog, 2011)

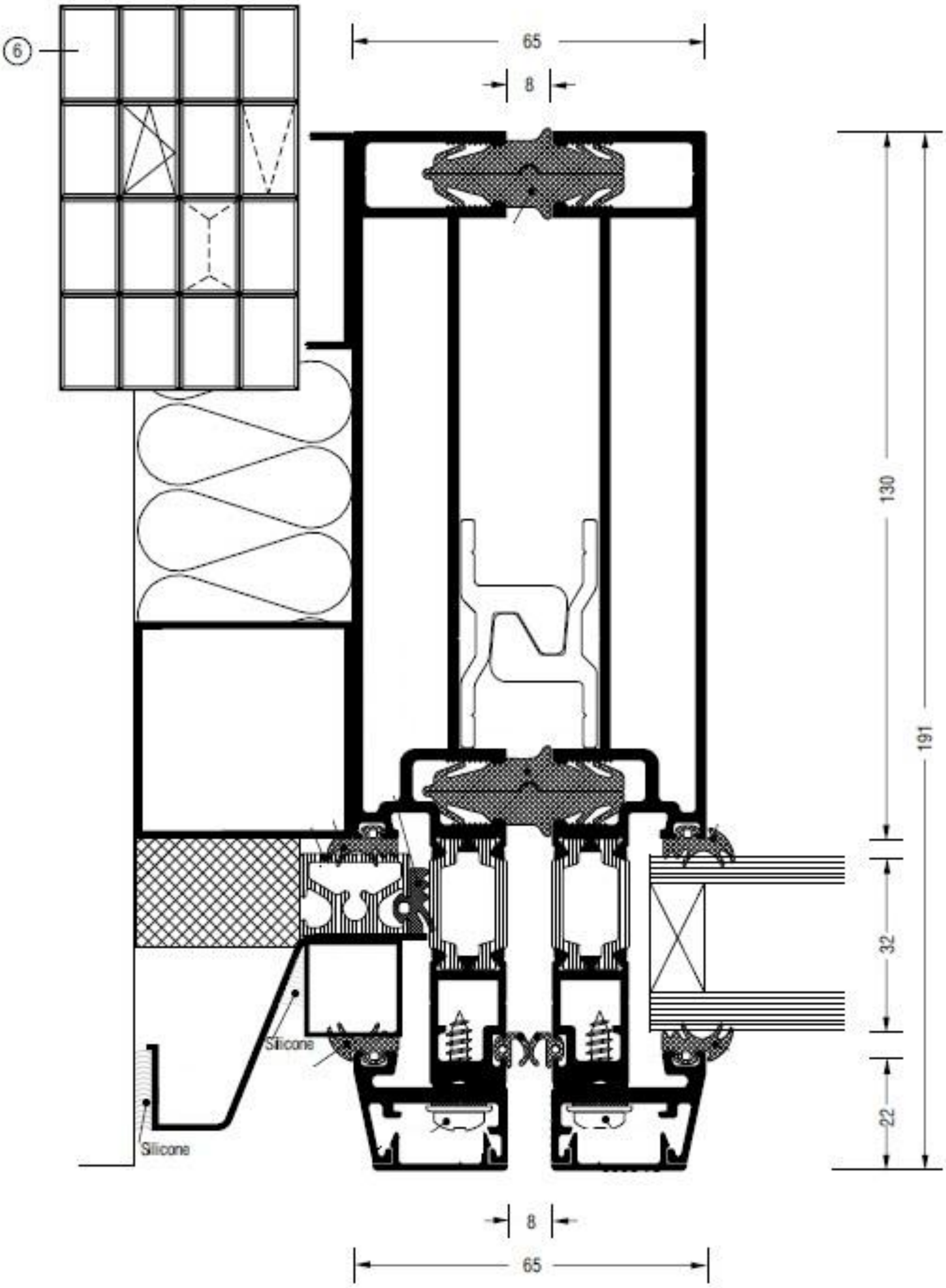


Figure A.6. The Detail of Vertical Member At The Wall Connection
(Source: Alumil Curtain Wall Catalog, 2011)

APPENDIX B

THE EXAMPLES OF BUILDINGS CONSTRUCTED WITH ALUMINIUM PANEL CURTAIN WALL SYSTEM

1) CCTV Headquarters, Beijing, China

Completion Year: 2012
Designer: OMA Architects
Tower 1: 234 m, 54 Floors
Tower 2: 210 m, 44 Floors
Curtain Wall Area: 110.000 m²

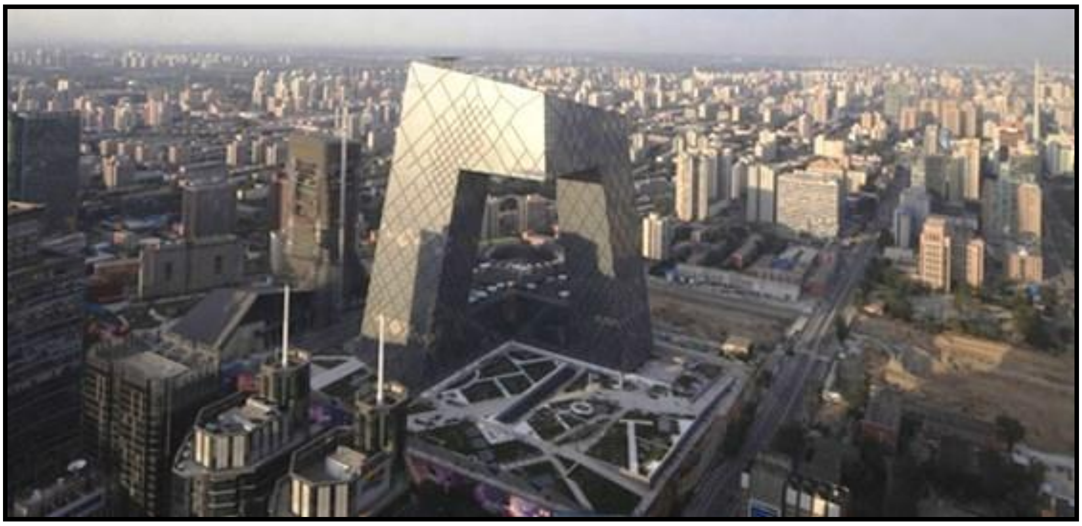


Figure B.1. The Photo from CCTV Headquarters (Source: http://oma.eu/,2012)

Figure B.2. The View from The Construction Stage of The Building (www.janghogroup.com,2012)

2) Infinity Tower, Dubai

Completion Year: 2010
Number of Stories: 73
Curtain Wall Area: 70.000 m²

Designer: SOM Architects
Buildign Height: 307 m

Figure B.3. The Views from The Construction Stage of The Building (www.janghogroup.com,2012)

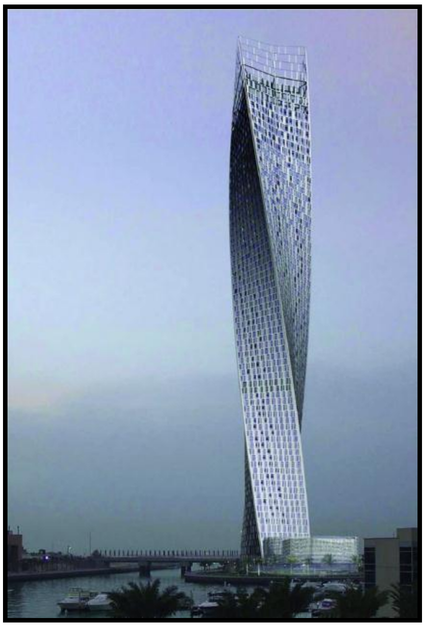


Figure B.4. The Render from Infinity Tower (www.janghogroup.com,2012)

3) China World Trade Center III, Beijing ,China

Completion Year: 2009
Designer: SOM Architects
Number of Stories: 83 (Including Basement)
Building Height: 330 m

Figure B.5. The Photo from China World Trade Center (Source: www.som.com,2012)

Figure B.6. The Detail from Curtain Wall Sysytem (Source: www.som.com,2012)

4) **Ocean Height Rezidence, Dubai**

Completion Year: 2010
Number of Stories: 83

Designer: AEDAS Architects
Building Height: 310 m

Figure B.7. The View from The Construction Stage of The Building
(Source:www.constructionweekonline.com,2012)

Figure B.8. The Photo from The Ocean Height Rezidence (Source: www.skyscapercity.com,2012)

5) Next Level Office Tower, Ankara, Turkey

Completion Year: Under Construction
Number of Stories: 32
Designer: Brigitt Weber Architects
Building Height: 115 m

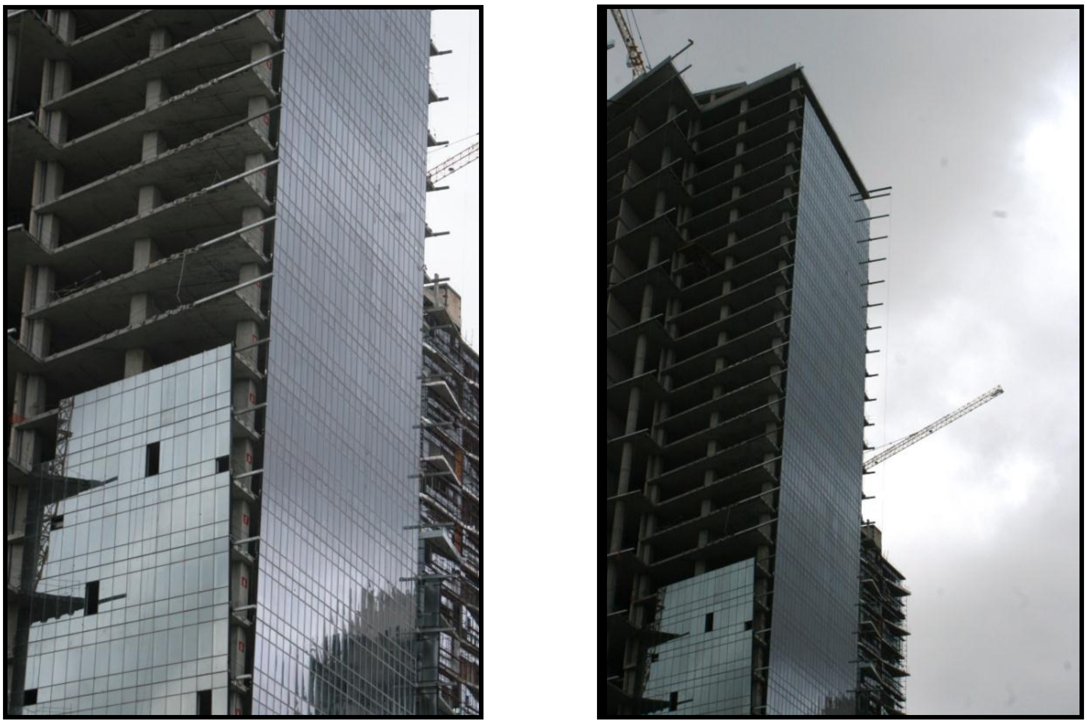


Figure B.9. The Photos from The Construction Stage of The Building
(Source:Individual Archive of The Author, 2012)

Figure B.10. The Photo from The Construction Stage of The Building
(Source:www.nextlevel.com,2012)

6) JW Marriot Hotel, Ankara,Turkey

Completion Year: 2012 **Designer:** Rmjm Hillier Architects
Number of Stories:24 **Building Height:** 90 m

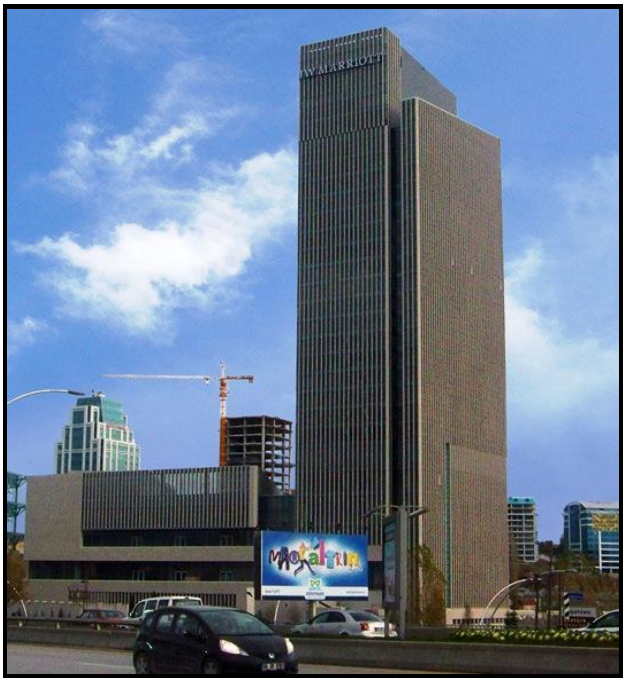


Figure B.11. The Photo from JW Marriot Hotel. (Source:www.rmjm.com, 2012)

Figure B.12. The Detail from Curtain Wall System. (Source:www.rmjm.com, 2012)