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A Balancing Act for the Curtain-Wall Design
幕墙设计的平衡之道

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This chapter provides a general overview of designing the curtain wall system of a high-rise structure. The past years have borne witness to the transformation of the construction industry - from conventional to modern and more importantly to vertical construction. With today's structures reaching for the skies, there are new challenges that need to be met, especially in terms of energy efficiency and structural integrity. The same can be said for curtain-wall systems. Factors such as aesthetics, performance and integrity of the curtain wall are subjected to meticulous tests and investigation so as to ensure building/curtain wall problems can be avoided in the future. This chapter tackles the principles of different material selection, building codes and relevant requirements, as well as the working relations of the people responsible for the curtain-wall design of the Ping An Finance Center (PAFC). Three arguments on the curtain-wall design of high-rise buildings, particularly with respect to the PAFC, will be discussed with corresponding resolutions.

本文对超高层建筑的幕墙系统设计提供全面的介绍。过去这些年来建筑业经历了重大的转折，由传统 (常规) 设计发展至现代设计，以及在高层建筑方面取得突破。随着建筑物向天空延伸的发展趋势，高层建筑需要面对更多新挑战，尤其是能源效能及结构完整性的要求。幕墙系统也正面临同样的挑战。为了预防建筑物/幕墙建成后可能产生的问题，设计师需要就美观性、性能及完整性等因素进行精确的测试和调查。本文为平安金融中心 (PAFC) 进行个案研究，阐述物料选择的准则、建筑规范及相关要求和幕墙设计人员的工作关系。总括而言，本文将以PAFC为例探讨三项有关超高层大楼幕墙设计的议题及其解决方法。

Introduction

The curtain-wall industry is on a seemingly perpetual tightrope – balancing one issue with the other. It must roll with the punches on a daily basis in the constant pursuit to innovate with better approaches to curtain-wall system efficiency and overall structural welfare/integrity. The principle of curtain-wall stands in contrast to the adage, "Beauty is only skin deep" since the curtain-wall doesn't just end with aesthetics, as many believe. There is so much more to it than meets the eye. This discussion aims to shed some light on some pertinent questions in reference to the Ping An Finance Center, as well as discuss the design and analysis of the curtain-wall system of the aforementioned.

Leaving no stone unturned, a brief account on the basics of curtain-walls is provided for the benefit of those aspiring architects and engineers who may have not yet been acquainted with the finer details of construction, fabrication, and installation of curtain-walls.

Curtain-wall (CW) is a term used to describe the exterior "skin" of a building. Curtain-walls can be made up of different materials such as glass, aluminum, stone, etc. It does not support any dead load from the main structure. The CW only supports its own weight and the exterior forces acting on it. These loads are then transferred to the main structure through anchors, brackets, and embedment. This chapter will focus on the most commonly used and applicable CW systems of today's high-rises. CWs started with the stick system, when all of the assembly and construction was done onsite. This system is still being used to this day. However, the CW system has evolved into what is commonly used and known as the unitized system. This type of CW system was used at PAFC.

PAFC CW System Overview

The unitized curtain-wall of PAFC (see Figure 4.1) was generally designed for two main purposes: First, to enhance the exterior architectural outlook of the structure while differentiating it from its surrounding structures and second, to withstand inevitable external environmental factors such as air and rainwater infiltration, wind forces, seismic activities and heat transfer. The

前言

幕墙行业从业员的工作如同走钢索一样，时刻需要平衡各项不同事项。每天在不断追求创新的过程中保持灵活应对，以确保用更好的方式提高幕墙系统的效率/效益和整体结构的完整性。有句谚语说"美貌不过一张皮"，设计幕墙的原则正好与之相反，因为幕墙系统并不如普遍观念一样只追求外观，同时也注重功能性。本文的目的是透过讨论及分析平安金融中心的幕墙设计，探讨有关建造巨型建筑的问题。

为了让尚未熟悉幕墙工程的建筑师和工程师了解更多有关幕墙工程、加工和安装的知识，本文将提供幕墙工程的基本介绍。

幕墙 (CW) 一词形容建筑物的"皮肤"，有时亦被解作建筑物的"外墙围护"。幕墙可由不同的建造材料建造，如玻璃、铝和石材等。幕墙不承受任何主体结构的荷载，只承受本身的自重和外力，而这些荷载会透过锚固件、支架及预埋件传递至建筑物的主体结构。本文将针对当今超高层项目常用的幕墙系统。早期的幕墙多为构件式幕墙系统，此系统在工地进行幕墙组装和施工，至今仍在不同项目中被使用。但是，近年单元式幕墙系统成为建筑幕墙普遍使用的系统。平安金融中心项目亦采用单元式幕墙系统。

design of the PAFC was envisaged as another balancing act between opposing elements.

There are five major wall types in the building. These are Wall Type 1, 2, 3, 8 and 9. In addition to that, there are three feature walls for the building. These are Wall Type 1.2, 2.2, and 7. Each wall type is discussed on the following pages.

Wall type 1 – WT1 or the Pier Wall (see Figure 4.2) is a unitized curtain-wall system situated in the four faces of the structure. It is a combination of transparent (vision) glass, opaque (shadow box) glass, and metal panel or stainless cladding. The wall has triangular horizontal fins or bullnoses on the glass walls that provide lighting pockets for the structure. The unique feature of the pier wall is the V-shaped metal panel wall that runs from the lower part of the structure up to the roof level. With the wide variety of options for material to be used for the metal panel, the final choice was stainless steel sheet.

WT2 or the Corner Wall (see Figure 4.3) is a unitized glass curtain-wall, which is the same type as the Pier Wall. Its unique feature is its stainless steel sheet panel that runs vertically along the structure in a zig-zag (chevron) direction as well as bullnoses, similar to that of the pier wall.

WT3 or the Mechanical Refuge wall (see Figure 4.4) is another unitized CW system that encloses the mechanical floor where the Heating, Ventilation and Air Conditioning (HVAC) systems of the structure are located. This covers an entirety of seven different levels in the total structure. The WT3 is a combination of glass louver in laminated glass for the exterior, and active louver on the interior.

WT8 Stainless Steel Cladding (see Figure 4.5A) and WT9 Stone Wall (see Figure 4.5B) are both unitized CW system forming the opaque panel of the structure. The architect initially meant for WT 8 & 9 to both be stone wall cladding; however the final design output resulted in separating the two WTs between level 26 and 27 due to code requirements (JGJ133-2001). WT9 is now a

Figure 4.1. Architect's renderings of the façade.
图4.1. 平安金融中心建筑图

平安金融中心 (PAFC)幕墙系统总览

平安金融中心的单元式幕墙系统 (见图4.1) 有两个主要目的: 第一，美化建筑物外表使其在周边建筑物中脱颖而出，第二是要承受/抵挡外来的环境因素，例如: 空气及雨水渗透、风荷载、地震活动和热传导。平安金融中心的设计可以被设想成兼顾各种不同要素的平衡之道。幕墙设计包含五种主要墙型: 墙型1、2、3、8和9; 及三种装饰墙: 墙型1.2、2.2和7。下文将对每种墙型进行介绍。

墙型1或墩墙 (见图4.2) 为单元式幕墙系统，位于建筑物的四个表面。该墙型包含透明玻璃 (可视玻璃) 、不透明玻璃 (背衬箱) 和金属板或不锈钢覆板。玻璃墙身上有三角形横向翅片或遮阳板，为建筑物的灯光装置提供支架。墩墙的设计特点为由建筑物底部伸延至楼顶的V形金属板。在众多金属材料中，建筑师选择了不锈钢作为板材。

墙型2或转角墙 (见图4.3) 与墩墙同样为单元式幕墙系统。设计特点为在建筑物以锯齿形方向垂直向上延伸的不锈钢金属板 (称为山形袖章) ，与墩墙的遮阳板设计相近。

墙型3或电机避难层 (见图4.4) 为另一个单元式幕墙系统，把置有暖通空调 (HVAC) 系统的电机层围起。此系统被应用于建筑物中的七个不同楼层。墙型3的外面由夹胶玻璃制成的百叶组成，而另一面由通风百叶组成。

墙型8的不锈钢外墙 (见图4.5A) 和墙型9的石材外墙 (见图4.5B) 同为单元式幕墙系统。建筑师最初选择石材作为墙型8和墙型9的材料，但由于要符合规范JGJ133-2001的要求，最终要把设计在26和27层分为2个墙型。墙型9为由建筑物底部一直向上伸延至123.8米高的石墙，而墙型8为由墙型9以上开始至平安金融中心楼顶的不锈钢外墙。

墙型1.2观景台 (见图4.6A) 和墙型2.2钻石墙 (见图4.6B) 两个装饰墙型皆为大楼顶部提供由大面积玻璃组成的可视区域，而第三种装饰墙墙型7 (见图4.6C) 则为覆盖大楼最高的钢框架的不锈钢板外墙。

平安金融中心的设计考虑因素

幕墙设计需要考虑到各项为建筑物带来影响的外部因素，这些因素成为幕墙结构设计主要关注的重点，如结构可行性、建筑物位移、性能和玻璃。

Figure 4.2. Wall Type 1 - Pier Wall
图4.2. 墙型1—墩墙

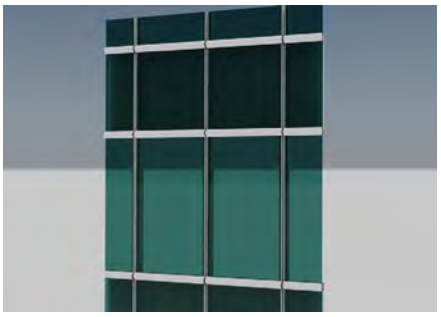

Figure 4.3. Wall Type 2 - Corner Wall
图4.3. 墙型2—转角墙

Figure 4.4. Wall Type 3 - Refuge Mechanical Wall
图4.4. 墙型3—避难和电机层墙

stone wall which runs from the base of the structure up to 123.8 meters high, while WT8 is stainless steel cladding, starting from the top part of WT9 all the way up to the roof.

The two feature walls, WT 1.2 Observation Deck (see Figure 4.6A) and WT2.2 Diamond wall (see Figure 4.6B) both provide a wide vision glass area at the top of the structure, while the third feature wall, WT7 (see Figure 4.6C) provides the topmost structural steel frame; it is clad in stainless steel sheets.

PAFC Design Considerations

The curtain-wall design considers different external factors that act upon the building. These external forces contribute to what becomes the major concern in designing the CW system of the structure, namely: structural feasibility, building movement, and performance of the glass.

Structural Feasibility

As previously mentioned, the ability to withstand forces of nature such as wind load, gravity load, seismic load and thermal load is of utmost importance in a curtain-wall. These factors dictate the material type, thickness, size and physical property of the CW system. Structural failure will endanger the lives of people near the curtain-wall.

"Wind load" is the term used to refer to the lateral forces experienced by the glazing and cladding material supported by framing members. The wind load is regarded as the main source of curtain-wall stress and deflection. To resist the high wind load, two supporting brackets were provided to support the frames of the Ping An's CW.

Temperature creates two issues in CW design. First is the expansion and contraction of materials (thermal expansions/ movement). Second is the necessity to control the passage of heat through the wall (thermal conductivity). Thermal expansion is included in the tolerances provided for the Ping An's CW system.

Gravity, unlike the other forces, is static and constant, often considered as the load due

结构可行性

如之前所述，幕墙设计最重要的因素是能够抵挡风荷载、地震荷载和热能。这些因素会影响物料的种类、尺寸和物理性质。结构破坏会给在幕墙附近生活的人们带来生命危险。

风荷载一词指由被框架构件支撑的玻璃和外墙物料承受的侧向荷载。风荷载是建筑幕墙设计中的主要荷载，因过强的风速会为幕墙产生的压力甚至破坏。而为了抵抗高风压，平安金融中心采用了双支幕墙框架。

温度为幕墙设计带来两个问题。第一是造成物料膨胀和收缩 (热膨胀/位移)；第二是要控制通过墙身传导的热力/能 (热导率)。热膨胀已考虑在平安金融中心幕墙系统内。

与其他力不同，引力是静态与恒定的，是由自重引起的荷载。引力会导致横向承重构件变形，特别是当构件须承受大块的重玻璃和金属板时。虽然相对其他因素，引力的影响较少，但长远来说，引力对外墙有重要的影响，故设计师必须作出适当处理。

建筑物位移

建筑物位移是其中一项最重要的考虑因素，但经常在设计铝外墙时被忽略。位移指当幕

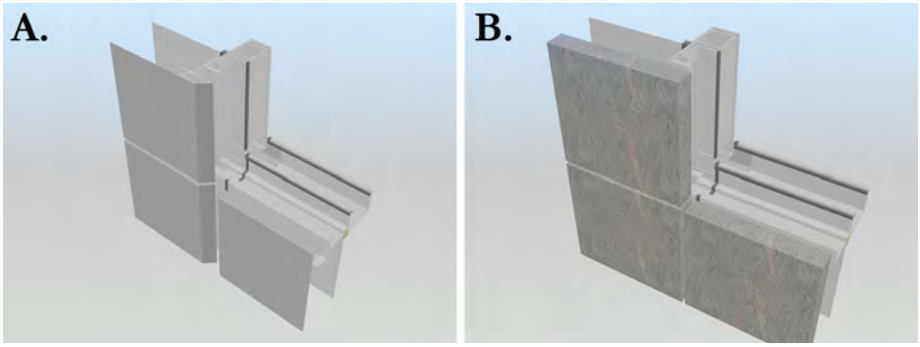

Figure 4.5. A. Wall Type 8 - Stainless Steel cladding, B. Wall Type 9 - Stone cladding
图4.5.墙型8—不锈钢外墙和墙型9 - 石材外墙

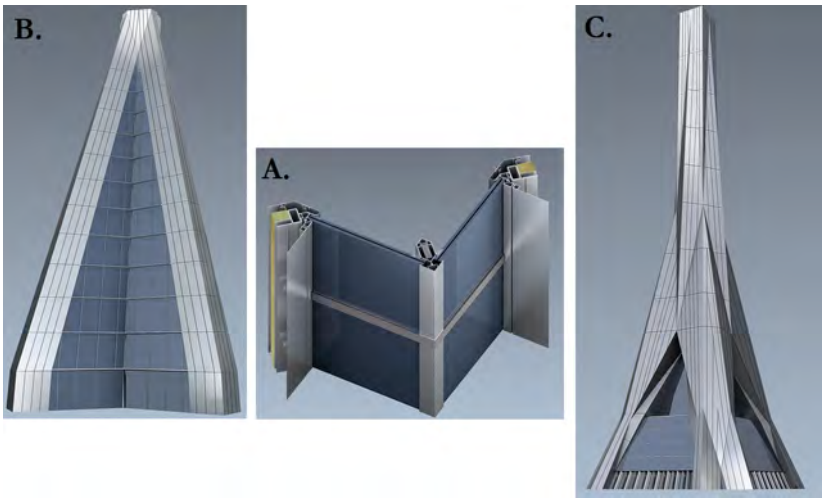

Figure 4.6. Feature Walls (A. Wall Type 1.2, B. Wall Type 2.2, C. Wall Type 7)
图4.6. 装饰墙 (A. 墙型1.2，B. 墙型2.2，C. 墙型7)

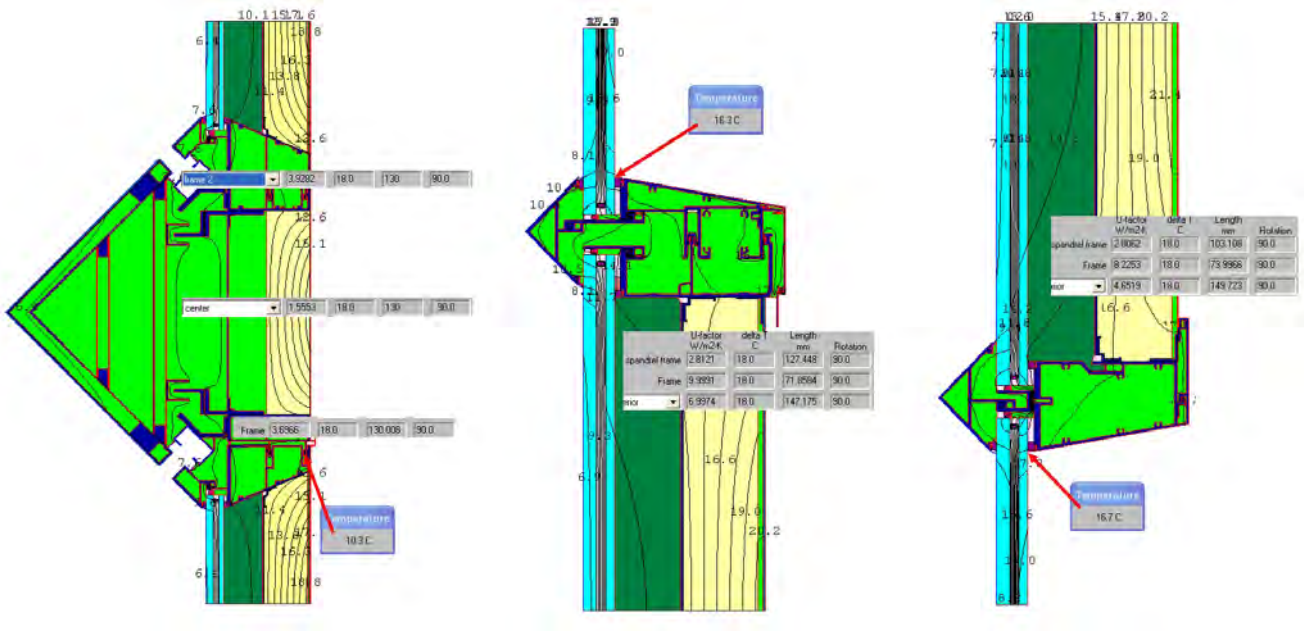

Figure 4.7. Thermal analysis result for the curtain wall system
图4.7. PAFC幕墙系统的热工分析结果

to self-weight. It causes deflections in horizontal load-carrying members, especially under the weight of large sheets of heavy glass and metal panels. Such deflections must be given proper consideration, as they could be detrimental to the cladding material in the long run.

Building Movement

Building movement is one of the most important considerations in designing any aluminum CW, but is often neglected. It is a constant movement of the main structure, concrete columns, relative movement between concrete slabs, and other structural components where the CW is attached. These are caused by thermal changes, wind action, gravity forces and deformations or displacements in the building frame. To disregard this potential is an invitation for trouble. These can be addressed by proper designing of joints, where a provision for both vertical and horizontal movement is factored in.

Performance

The performance of the CW pertains to weathertightness due to weather conditions. There are a handful of environmental elements that need to be considered, but in countries such as China, specifically the southern tropical parts, sunlight, water and moisture, temperature and sound are the major factors.

Sunlight provides warmth, color, visual definition and life itself. However, it can also pose a problem in CW design, such as its deteriorating effect on finishes, polymers, and sealants. Ultraviolet rays induce chemical reactions that cause fading or serious degradation of materials. When sunlight passes through the wall, it could bring discomfort from glare and degradation of interior furnishings. Therefore, it is essential to ensure that materials and finishes vulnerable to light be thoroughly investigated before use. Sealants must be tested for resistance to changes in temperature and UV radiation.

Water is probably the most tenacious problem of them all. Wind-driven rain can enter very small openings and may move within the wall. In the form of water vapor, water can penetrate microscopic pores and later condense upon cooling. If trapped within the wall, it may cause serious damage that could long remain undetected and could lead to corrosion. Some of the water may penetrate the wall, appearing as leaks on the interior.

Thermal conductivity or heat flow is another major design consideration. A system design to prevent condensation in cold weather or to minimize heat gain and air-conditioning costs in hot weather is usually a good long-term investment. Materials such as metals and glass all have high thermal conductivity. With proper attention to detail, aluminum curtain-walls can provide good thermal performance. This is accomplished by minimizing the proportion of metal framing members exposed to the outdoors, eliminating short circuits by adding thermal isolators and breaks, using double glazing or an insulating glass unit (IGU), and providing good insulation. Thermal analysis is done to check the Thermal conductivity of the curtain-wall system (see Figure 4.7).

Under normal conditions, even in densely built urban areas, CWs act as a barrier to airborne sound and prevens sound transmission. Due increased concerns about noise pollution, the

墙挂上主结构后引起主结构、混凝土柱、混凝土板之间的相对位移。位移一般由温度变化、风力作用、引力、结构变形/挠曲或结构框架的位移引起。故忽略位移因素会为工程带来不良影响。建筑位移可透过适当设计接缝使其能够容纳/承受垂直和横向位移。

性能

幕墙的性能及其耐候性需针对气候状况。在不同国家需要考虑不同的环境因素，但在中国南方热带地区，主要需要考量的因素为日照、降水、湿度、温度和声音。

阳光为我们提供温暖、颜色、视觉分辨和生命，但同时会为幕墙设计带来问题，因为阳光会导致表面涂层/处理、聚合物和硅胶出现褪色。紫外线引起的化学作用会导致物料褪色或严重老化。当阳光穿透外墙时会产生刺眼的光线，亦会令室内表面的涂层老化和褪色。因此在选用物料前必须对其耐用度进行彻底研究，如对硅胶必须先进行有关温度变化和紫外线的测试。

水是众多因素中最为重要的一项，当风把雨水吹进幕墙内的小孔后，产生微细孔作用，在温度高时蒸发成水蒸气，冷却时凝结成液体，故水可以长时间留在幕墙内而不被察觉，并可能导致生锈，使幕墙受到破坏，部分水分穿过幕墙会导致漏水。

热传导是另一个幕墙设计需要考虑的重要因素，因幕墙设计是长远的投资，要能够有效防止幕墙在寒冷天气下结露，并减少炎热时大楼的空调费用。金属和玻璃等材料的热传导率十分高。要提升幕墙效能，设计时需要对铝外墙的细节进行适当处理，包括: 减少使用暴露在室外的金属组件，增加断热材料以阻隔热能，采用双层玻璃或中空玻璃 (IGU) 以提供良好的隔热物料。同时，需要完成热工分析以检查幕墙系统的传热性能 (见图4.7) 。

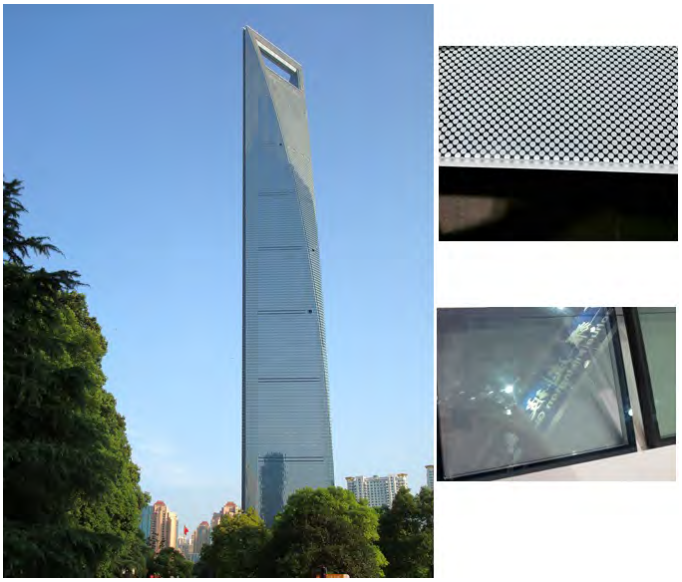

Figure 4.8. Glass curtain wall system (Shanghai World Finance Center, China)
图4.8. 玻璃幕墙系统 (中国上海环球金融中心)

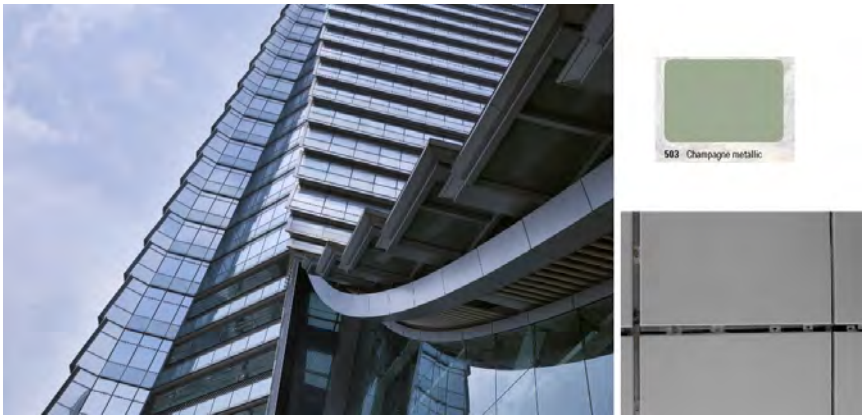

Figure 4.9. Aluminum panels lining a high-rise structure (International Commerce Center, Hong Kong)
图4.9. 高层建筑上的铝板 (香港环球贸易中心)

Figure 4.10. Building stone cladding (Building near Xintiandi, Shanghai)
图4.10. 石材外墙 (中国新天地项目)

在建筑密度高的市区地带，幕墙有阻隔声音和防止声音传播的作用。由于社会近来对噪音污染的关注日益增加，幕墙的隔音功能变得更为重要，若幕墙设计能关注隔音性能就能有效阻隔噪音。

外墙物料的种类和选择

玻璃

玻璃是单元式幕墙最常用的物料 (见图4.8)，这种物料经过浮法工序制造而成。如果需要强度或安全性更高的玻璃，可以选择使用半钢化、钢化和夹胶玻璃。玻璃的厚度范围为由6mm至22mm。幕墙的可视玻璃一般为透明的单片玻璃或中空玻璃，人们能透过玻璃看到建筑物的表面/外部。中空玻璃能有效控制热传导，标准的中空玻璃由两片玻璃及其之间的空气层组成。建筑师或设计师一般会在可视区采用Low-E膜以提高中空玻璃的性能。在平安项目的设计中，使用外片为夹胶玻璃，内片为单片玻璃的中空玻璃作窗间墙玻璃，在中空玻璃后90mm设置铝背衬箱。

铝

铝的耐用度高，设计可塑性强且美观，故经常被用于幕墙系统 (见图4.9)。为了兼顾铝材的功能性和美观性，铝材必须经表面处理以提高其颜色和预防任何衬色、变质、凹痕、瑕疵/缺口或提早老化。其中最常用的两种表面涂层方法，分别是液体喷涂和粉末喷涂。液体喷涂通常指PVDF (氟碳喷涂)，由70%的PVDF及30%的树脂组成; 而粉末喷涂则由聚脂树脂制造，粉末喷涂为高规格喷涂料，坚固及损耗度低，但容易因紫外线/阳光中的有害光线导致褪色，一般在室内或不暴露在阳光下的室外范围使用。平安金融中心的室外框架使用PVDF作表面处理，在室内则采用粉末喷涂。

不锈钢

不锈钢为由铬和铁组成的合金，其耐蚀度和耐染度高，且在被刮和磨蚀时具有"自愈"能力。不锈钢能进行不同的表面处理，如镜面、亚光面、压花和抛光面处理，但不会作漆涂处理。不锈钢可被使用于建筑物室内和室外，作为栏杆、门、板材、框架和楼顶的覆面板，并能为建筑物带来不同寻常的视觉效果。平安项目使用1.5mm厚的不锈钢板，虽然不锈钢的表面质量良好 (见图4.11)，但表面同时容易造

need for soundproofing the structure has become a major consideration in CW design. With careful design and understanding, CWs can be crafted to provide good acoustical performance.

Cladding Material Options and Selections

Glass

Unitized CWs often use glass (See Figure 4.8). Glass produced through the float glass process is annealed by its nature. If additional strength or safety is required, heat-strengthened, tempered, or laminated glass may be used. It is available in various thicknesses between 6 mm and 22 mm. Vision glass for a CW may be a single glass panel or IGU. It is generally transparent and often provides the vision on the exterior of the structure. It is usually assembled into an IGU to provide thermal conductivity control and better performance. Typical IGUs consist of two layers of glass with a spacer between the panes. The architect or designer usually specifies the IGUs for the vision area with a *low-e* coating material to increase the performance of the vision glass. On PAFC, the spandrel glass is an IGU with a laminated outer lite and a fully tempered monolithic glass. An aluminum sheet, 90 mm behind the IGU, provides the Shadow Box.

Aluminum

Aluminum is used for CWs due to its durability, design versatility, and aesthetic potential (see Figure 4.9). To be both functional and pleasing to the eye, it must be coated with a finish that enhances color and resists any fading, chalking, pitting, chipping or premature aging. Thus aluminum coating becomes necessary. There are two existing coatings that are widely used for aluminum: liquid coating and powder coating. Liquid coating, often referred to as PVDF (polyvinylidene flouride) coating, is formulated with 70% PVDF and 30% resin. Powder coating, on the other hand, uses polyester resin. This produces a high specification coating which is relatively hard, abrasion-resistant (depending on the specification) and tough, although it can easily fade due to the harmful rays coming from the sun. It is recommended that powder coating be used in the interior or on the exterior visually exposed. At PAFC, aluminum is used on framings with PVDF finishes on the exterior side, and powder coating on the interior and visually unexposed exterior framing.

Stainless Steel

Stainless steel is a metallic alloy combination of chromium and iron. It is known for its high resistance to corrosion, stains, and rust. It also has a "self-healing" property, when it is scratched or experiences abrasions. Stainless steel can come in different finishes – mirror, linen, embossed, or polished but it will not come with paints. Stainless steel for wall cladding can be used for both the exterior and interior of the building, creating a striking architectural effect, as well as for railings, door cladding, paneling, framing, and roof cladding. On PAFC, 1.5 mm-thick stainless steel is used for metal panels. Although stainless steel has a good quality finish (see Figure 4.11), it is very sensitive to denting. Fabricating a stainless steel panel requires intensive proper handling. At PAFC, ASTM A666 or GB/T 1220 stainless steel sheeting with linen finish was used.

Stone

Stone is a naturally occurring material and is good for architectural purposes. Stone cladding exhibits a classical yet strong expression (see Figure 4.10). When selecting stone for glazing material, different factors that affect the production should be taken into consideration. Physical properties such as geological classification, texture, and fabrication soundness and production size mostly contribute to the aesthetic character, while the mechanical properties of the stone contribute to the technical and structural capacity of the stone. In PAFC, a single quarry site was employed as the source of the stone to maintain the consistency of each stone produced. Certain processing or finishing can only be done on certain types of stone. Stone surfaces can be finished in a number of ways that may satisfy the design intent of a structure. Size is often the limiting factor when selecting stone. Increasing the size of stone is not always economically

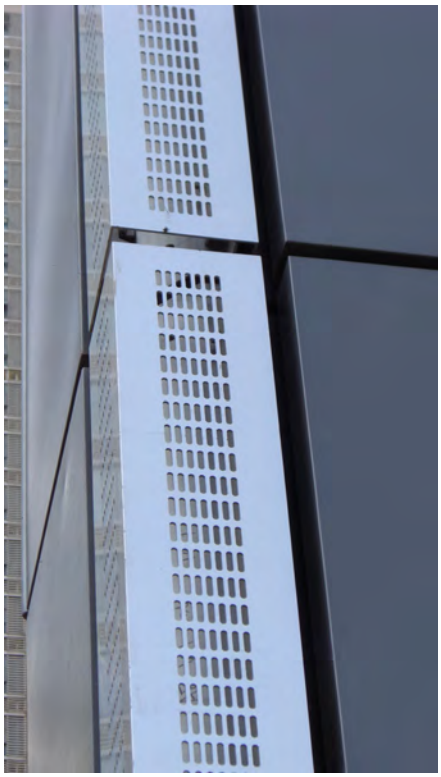

Figure 4.11. Stainless steel cladding for visual mock up
图4.11. 视觉样板的不锈钢外墙

成凹痕，故加工时需小心处理。在平安项目中使用的不锈钢材为ASTM A666或GB/T 1220钢板，表面为亚光面。

石材

石材是经过长时间的自然作用产生的天然建筑材料。石材外墙能为建筑物营造强烈的效果 (见图4.10) 。在选用石材作为幕墙物料时需考虑影响生产工序的不同因素。物理性质如地质分类、材质、纹理、正确加工和生产规模都会对石材的美观度构成影响; 而机械性质则影响石材结构的承受能力。平安项目使用的石材来自同一个矿场，使每块石材的连贯性得以保持。不同的石材需使用不同的表面加工工序，以满足建筑物的设计理念。石材的限制性因素是尺寸，尺寸越大，造价越高，故使用石材时须考虑其结构承受能力和价钱，平安项目的低层范围以石材为主要外墙物料。

铝塑板 (ACP)

铝塑板是能够融合视觉效果和结构要求的建筑物料 (见图4.12) 。其主要好处是重量轻而且坚固，颜色选择多样化，甚至可以塑造自然素材 (如木和石) 的颜色。此物

Figure 4.12. Aluminum composite panel for curtain wall cladding (Sky City, Taiwan, China)
图4.12. 铝塑板外墙 (台湾天空之城)

feasible. It will always depend on the structural capacity and the economic value of the stone type to be used. Stone is the primary cladding material of choice for the lower floors of PAFC.

Aluminum Composite Panel (ACP)

Aluminum composite panels present an alternative building material that combines visual appearance and structural demands in the best possible way (see Figure 4.12). Its main advantage is its light weight, rigidity and strength. The color variety of aluminum composite panels is so extensive that even natural colors such as a wood and stone can be duplicated. The material is composed of two aluminum sheets bonded by a polyethylene core that is resistant to weather. The ACP was included in the material selection process for PAFC, but was later disregarded because a solid aluminum sheet was still preferred.

Terra Cotta

Generally, the broadest definition of terra cotta refers to a high-grade weathered or aged clay which, when mixed with sand or with pulverized fired clay, can be molded and fired at high temperatures to a hardness and compactness not obtainable with brick. Terra cotta usually consists of hollow-cast blocks which are open at the back, like boxes, with internal compartment-like stiffeners called "webbing," which substantially strengthens the load-bearing capacity of the hollow terra-cotta block without greatly increasing its weight. For walls with higher and longer modulation, terra cotta can be customized to fit the architectural need (see Figure 4.13). However, increase in size will affect the structural performance of the terra cotta and additional structural support must be provided. Thus, the cost of several important components will rise. Also, the material should be tested if the size is customized to accommodate larger panels. Terra cotta provides a wide range of color, texture, and product. Because of the natural color of the clay, the color is not commonly affected by the environment. Terra cotta was removed from consideration for PAFC because stone cladding was still preferred; terra cotta was not able to meet the architect's visual intent.

Glass Fiber Reinforced Concretes (GFRCs)

GFRCs are lightweight concrete compounds modified with additives and reinforced with glass fibers. They are generally fabricated as thin-shelled panels and applied to a separate structural frame or anchorage system. The GFRC is most commonly sprayed into shapes, although it can be poured. The glass must be alkaline-resistant to avoid deteriorating effects caused by the cement mix. The color is derived from natural aggregates, and if necessary, a small percentage of added pigments (see Figure 4.14). The GFRC main ingredients are concrete Portland cement, aggregates of selected crushed stone or silica sand, glass fibers, and polymers that improve toughness. Initially, GFRC was also considered in the material selection process but, stone prevailed as the material of choice, as GFRC was not able to meet the architect's visual intent.

Building Codes and Requirements

The Chinese National Bureau of Standards created a hierarchical set of codes. These are often referred to as "GB standards." They are consistent across all of China and are developed for technical requirements. The GB stands for Guobiao.

Wind Load Value Consideration

One of the fundamentals of glass selection, glass computation, and frame sizing is to

料由两块铝板加上耐候性高的聚乙烯粘合而成。平安项目原先选择铝塑板作物料之一，但其后因铝板较符合要求而被弃用。

陶土板

陶土板，指以耐候土壤和沙或土壤粉末混合，再经高温烧制和高压挤出成型的坚固而轻巧的物料。陶土板通常为中空设计，像盒子一样开在后方开口，内部装有轻巧的加强肋承受荷载。陶土板可以根据不同的建筑风格进行任意切割 (见图4.13) 。但是，增加陶土板尺寸会影响结构承受能力，需要为陶士板加上额外结构支撑。陶土板的颜色、材质和产品种类繁多，而且其颜色为天然颜色，不易被环境影响。平安项目并未采用陶土板，因不符合建筑师的视觉要求，故未被使用。

玻璃纤维混凝土 (GFRC)

玻璃纤维混凝土是用水泥沙浆混合玻璃纤维以增加其强度的混合材料。主要用于独立结构上的薄板或锚固系统上。虽然玻璃纤维混凝土可以以灌注工艺涂上表面，但常用做法是将配制好的玻璃纤维混凝土喷射在模板上。在玻璃纤维混凝土中使用的纤维必须是抗碱玻璃纤维，以抵抗混凝土对玻璃纤维的侵蚀。GFRC的颜色取决于其原料颜色，亦可通过加入少量色粉调整颜色 (见图4.14) 。玻璃纤维混凝土主要材料为硅酸盐混凝土，混合碎石或硅砂，玻璃纤维和用来增加强度的聚合物制成。与陶土板一样，玻璃纤维混凝土因不符合建筑师的视觉要求，故未在平安项目中使用。

建筑规范及要求

国家标准局订立了一套建筑规范，简称国标，为中国各地提供建筑技术层面的要求。

风压值

一个地区的风压值特性是决定玻璃类型、配置和框架尺寸的重要因素。风压的大小取决于多项因素，如建筑物的高度、建筑物的所在地及位置和建筑物周围的建筑物。中国建筑科学研究院进行了一系列的测试、实验和收集数据以制订国标对风荷载的规范。国标利用建筑物的高度及其所在地计算风荷载。由于平安金融中心的高度达660米，故以国标得出的风压值非常高。

根据国标玻璃幕墙工程技术规范JGJ102-2003中的第5.3.3条，玻璃幕墙的风荷载标准值可按风洞试验结果确定; 玻璃幕墙高度大于200米或体型、风荷载环境复杂时，宜进行风洞试验确定风荷载。风洞试验能预测计算或规范不能测量到幕墙的热点。

平安项目委托Rowan Williams Davies & Irwin Inc. (RWDI) 风洞试验室进行试验，RWDI

Figure 4.13. Curtain wall cladding with terra cotta (Beijing Huamao Center, China)
图4.13. 陶土板外墙 (中国北京国贸中心)

Figure 4.14. Glass fiber reinforced concrete cladding material (Songdo, South Korea)
图4.14. 外墙物料玻璃纤维混凝土 (南韩首尔Songdo项目)

identify the wind load characteristics existing within a region. The wind load condition may vary depending on the height of the structure, the location of the structure, and by existing barriers near. The China Academy of Building Research (CABR) conducted a series of experiments to come up with the GB Code for wind load. GB Code for wind load is dependent on the height and area or location of the structure. Because PAFC is a 660-meter tower, the wind load computed using the GB Code resulted to a high wind pressure.

Furthermore, GB Code for Glass Curtain-wall Engineering (JGJ102-2003), article 5.3.3 states the wind loading of the glass curtain-wall should coincide with the wind tunnel test result. If the curtain-wall height is more than 200 meters or the building shape and/or wind environment condition is too complex, the wind tunnel test is a better wind loading determinant. A wind tunnel test can predict hot spots on a curtain-wall that cannot be detected through calculations or codes.

For the PAFC project, Rowan Williams Davies & Irwin Inc. (RWDI), the wind tunnel test provider, used the 100-year return period (see Figure 4.15). The color indicated in the wind tunnel test result illustrates the zoning done to identify the glass makeup that was used for the wind load value. GB Load Code for the Design of Building Structures - Article Explanation (GB5009-2001), Article 7.1.2 states: with regards to the envelopment of the structure, the loading should be tested for a 50-year return period. RWDI recommend a reducing factor of 88% to safely reduce the wind load to a 50 year return for the PAFC.

Metal and Stone Cladding Engineering

The Technical Code for Metal and Stone CW Engineering, JGJ133-2001, did not specify the height limitation of stone and metal cladding CW. However, it is stated that the code only applies to building heights of less than 150 meters, and it should be located at areas where the seismic fortification intensity is less than level 8. If the building height exceeds the limitation, the code will not be applicable. The PAFC height extends 660 meters above the ground. Since the stone cladding of the building is restricted to a height of 150 meters, JGJ133-2001 can be used as a supporting design tool (see Figure 4.16).

使用100年重现期进行试验 (见图4.15) 。风洞试验结果内以颜色区分不同风压值使用的玻璃配置。国标建筑结构荷载规范GB5009-2001说明中的第7.1.2条，可按照建筑物护围的结构采用50年一遇的风压。RWDI建议把折减因子定为88%，以把平安金融中心的风压减低至50年一遇的风压。

金属和石材外墙工程

金属与石材幕墙工程技术规范JGJ133-2001中并没有明确指出石材和金属外墙的高度限制。但是，规范只适用于高度低于150米和位于抗震设防烈度小于第8级的建筑物，若建筑物超过前上述条件，则规范对于石材外墙设计、安装和检查的指引将不再适用。因平安金融中心的高度达660米，故石材外墙只能限制于150米以下，以符合设计规范的要求又同时可以沿用JGJ133-2001作设计指引 (见图4.16) 。

安全玻璃设计

在中国，国标要求所有幕墙设计必须使用安全玻璃。常见的安全玻璃种类有钢化玻璃和夹胶玻璃。表格4.1为两种玻璃的对比。

钢化玻璃属于安全玻璃的其中一种，通常使用在普通玻璃有潜在使用危险的地方被使用。钢化玻璃的冲击强度是普通玻璃的

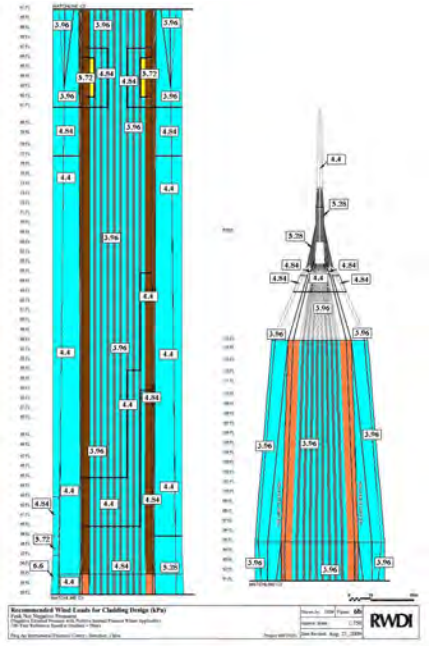

Figure 4.15. Illustration from wind tunnel test study (RWDI, 2009)
图4.15. 风洞试验研究图 (RWDI，2009)

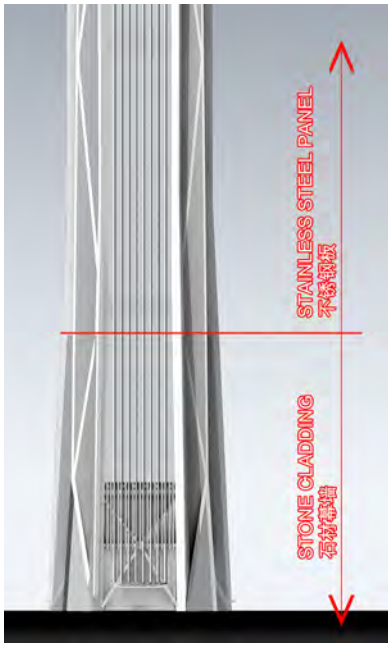

Figure 4.16. Stone Cladding and Stainless Steel Panel Interface
图4.16. 石材外墙和不锈钢板

Safety Glass Design

In China, the GB Code curtain-wall design only allows the use of safety glass. It can be in a form of fully tempered glass or laminated glass. Table 4.1 tabulates the comparison between two safety glasses.

Tempered glass is one of two kinds of safety glass regularly used in applications in which standard glass could pose a potential danger. Tempered glass is four to five times stronger than standard glass and does not break into sharp shards when it fails. Tempered glass is manufactured through a process of extreme heating and rapid cooling, making it stronger than normal glass. The brittle nature of tempered glass causes it to shatter into small oval-shaped pebbles when broken. Check local codes before implementing.

Laminated glass is traditionally defined as 1) Two or more lites of glass and one or more interlayers of plasticized polyvinyl butyral (PVB) permanently bonded together under heat and pressure, 2) Two or more lites of glass and polycarbonate with an aliphatic urethane interlayers between glass and polycarbonate permanently bonded together under heat and pressure, or 3) Two or more lites of glass bonded with one or more interlayer of cured resin or other material. This union of materials provides a variety of performance benefits in architectural applications. Laminated glass' most important characteristic is the ability of the interlayer to support and hold the glass when broken. This provides for increased protection against fall-out and penetration of the opening, affording additional benefits such as increased wind loading strength, impact resistance and resistance of thermal stress (see Table 4.1).

Conclusion

As a conclusion to this chapter, the following items are offered as a summary of a CW design strategy for a high-rise structure.

1. Identify the different external elements and environmental factors that may exist. This will dictate the technical feasibility of the curtain-wall.
2. Select and evaluate the materials in the curtain-wall that can withstand the environment surrounding the building without sacrificing the aesthetics of the structure. The beauty of the curtain-wall creates a lasting statement for the building.
3. See to it that all the criteria of the building codes and design requirements are achieved or exceeded. These requirements will establish the safety, the efficiency, and durability of the curtain-wall.

No aspect should ever be deemed negligible when it comes to ensuring the overall performance and longevity of a building's curtain-wall, since these structures, once erected, will stand to outlast the average human's life span.

4至5倍，当玻璃受破坏时，碎片没有尖锐棱角。钢化玻璃经过极端加热，再进行快速均匀的冷却而制成，使其抗冲击强度比普通玻璃高。其特性使钢化玻璃受破坏时，碎片会成类似蜂窝状的钝角碎小颗粒。在建筑物采用钢化玻璃前应先检查各项规格和要求。

传统上夹胶玻璃被定义为: 1) 由两片或以上的玻璃和一层或以上的聚乙烯醇缩丁醛胶膜 (PVB)，经过高温高压工序处理后粘合; 2) 由两片或以上的玻璃和聚碳酸酯 (PC) 板，经脂肪族的聚氨酯二丙烯酸酯夹胶层高温高压处理后粘合; 3) 由两片或以上的玻璃和凝固树脂或其他物料粘合的玻璃产品。在建筑应用上夹胶玻璃在性能方面有多种好处，其特性为玻璃碎裂后碎片会被粘在薄膜上，能防止玻璃坠落、渗水和其他好处如增加风荷载承载力、冲击阻力及抗热应力 (见表4.1)。

结论

作为本文的总结，以下为高层建筑的幕墙设计需要考虑的各项因素之概要。

1. 识别各种可能存在的外力因素和环境因素，这些因素将影响幕墙的技术可行性。
2. 对幕墙使用的物料进行选择和评估，确保物料在不影响建筑物美观度的前提下抵挡周围的环境因素，因幕墙的美感帮助建筑物营造永恒整体的印象。
3. 确认设计符合所以有关的建筑物规范和设计要求，使幕墙实现安全、效能和耐用度方面的要求。

当中每一项因素均不能被忽略以保证幕墙的整体性能和耐用度，因为建筑物幕墙的寿命/使用年限与人的平均寿命相当。

Property and Requirements 性质和要求	Fully Tempered Glass 钢化玻璃	Laminated Glass 夹胶玻璃
Conforming Standard **适用的规范**	GB/T 9963 – Tempered Glass GB/T 9963 – 钢化玻璃	GB 9962 – Laminated Glass GB 9962 – 夹层玻璃
Structural Performance **结构性能**	Tempered glass can be 3-5 times the bending and impact strength of a normal annealed glass of the same thickness. 钢化玻璃的抗弯强度比同等厚度的普通浮法/退火玻璃高3 – 5倍。	Laminated glass is generally 75% to 90% as strong as annealed glass of same total thickness. 夹胶玻璃的强度比同等厚度的普通浮法/退火玻璃高75% – 90%。
Glass Performance **玻璃性能**	Coating can increase glass performance. 可以通过涂层处理增强玻璃性能。	Coating is applicable to increase glass performance with consideration of the PVB layer. 可以通过涂层处理和PVB夹胶层增强玻璃性能。
Safety **安全性**	When fully tempered glass breaks, the glass fractures into small, relatively harmless fragments. This kind of breakage can minimize injuries as there are no jagged edges or sharp shards. Due to this property, along with its strength, tempered glass is often referred to as safety glass (See Figure 18). 当钢化玻璃受破裂时，碎片为钝角碎小颗粒，这种碎片因其没有尖锐棱角而能减少玻璃对人体造成伤害 (见图18) 。	The interlayer keeps the layers of glass bonded even when the glass is broken, and its strength prevents the glass from falling away from the frame. This produces a characteristic "spider web" cracking pattern when the impact is not enough to completely pierce the glass (See Figure 19). 玻璃碎裂后夹胶膜碎片会被粘在薄膜上，防止玻璃由窗框坠下。若撞击力不足以击碎玻璃，玻璃将出现"蜘蛛网"状的碎裂形状 (见图19) 。
Architectural Property **建筑性能**	Tempered glass can exhibit a wavy pattern due to the tempering process. But modern technology has helped in reducing the wavy effect of tempered glass. 钢化玻璃可能会因加热工序出现波纹，但现代科技已可有效减少钢化玻璃出现波纹。	Since annealed and heat strengthened glass doesn't exhibit a wavy characteristic, laminated glass can be flat. 由于退火玻璃和半钢化玻璃不会出现波纹，故夹胶玻璃是平整的。
Cost Analysis **成本分析**	Main input for the cost for tempered glasses is the heat treatment or tempering. 成本主要来自加热处理工序。	The application of the bonding layer or PVB of the laminated glass is the main cost for laminated glass. 成本主要来自夹胶玻璃的夹胶层或PVB。
Potential Problem **潜在问题**	Spontaneous breakage of tempered glass 钢化玻璃有可能在无外力作用的情况下自爆。	The sudden thinning of the PVB layer or delamination. PVB夹层变薄或出现脱胶。
Precaution **预防措施**	Heat soak test or the destructive test applied for tempered glass to determine if glass is prone to spontaneous breakage. Tempered glass is stored in a heating chamber for 8 hours at 280 ºC to 300 ºC. 为钢化玻璃进行均质处理，将钢化玻璃加热到280℃至300℃，并保温8小时，以提前确认有可能自爆的玻璃。 As for the spontaneous breakage concern, a 100% heat soak for tempered glass is recommended. 为了预防钢化玻璃自爆，ALT建议为100%钢化玻璃进行热浸处理。	Using PVB interlayer, the edge of the laminated glass should be covered and sealed. 夹胶玻璃的边缘应作妥善的封边处理。

Table. 4.1 Comparison between Fully Tempered Glass and Laminated Glass
表格4.1钢化玻璃和夹胶玻璃的比较

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