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Post Breakage Strength Testing for Overhead Laminated Glass | 采光顶点式安装钢化夹层玻璃破碎后强度测试

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Ingo Stelzer是可乐丽PVB部门全球技术顾问组的负责人。他已在玻璃和幕墙行业工作15年，拥有很强的专业经验，参与了世界上许多工程和研发工作。他也是欧洲DIN & EN标准工作组的成员。 在加入可乐丽前，他曾经在杜邦GLS部门任职资深顾问和在德国Seele集团任职技术总监。在2000年，他在汉诺威工业大学毕业并获得工程学位。

Abstract | 摘要

The design and structural performance of laminated glass in glazing applications like canopies and skylights is very critical, as it has an impact on the safety of occupants in a building and maintenance workers. For such applications, the post breakage strength of laminated glass construction is of the utmost importance. Pre-breakage strength can be predicted with reasonable accuracy by FEM technique-based software, which allows the user to input the mechanical properties of interlayers along with glass. This helps in the interlayer-based differentiation of pre-breakage structural strength and design optimization. However, the post-breakage strength of glass is still an unknown area, as analytical models for this are inconclusive so far and thus destructive testing is the only reliable solution. Impact testing, simulating the accidental fall of a maintenance worker (prDIN 18808-6) was done to assess the "fall through" resistance of point fixed laminated glass constructions having varying interlayers at different temperature levels.

Keywords: Code Compliance, Design Process, Façade, Interlayer Materials, Laminated Safety Glass, Life Safety

在采光顶，雨棚和天窗的玻璃这样的装配应用中，夹层玻璃的设计和结构性能是非常关键的，会影响居住者和维修人员的人身安全。对于这样的应用，夹层玻璃结构破碎后强度至关重要。玻璃破碎前强度可以由有限元建模技术的软件进行合理准确的预估，使用者可以在该软件中输入粘弹性中间膜以及玻璃的力学性能指标。这有助于提高玻璃破碎前不同的夹层材料的结构性能并促进其设计优化。然而，玻璃破碎后的强度仍为未知领域，其分析模型仍无法确定，因此破坏性测试是测试它的唯一可靠解决方案。本报告将通过模拟一个维修工人意外坠落的冲击测试，来评估点式安装的不同中间膜夹层玻璃的玻璃破碎后性能。实验采用德国DIN 18008-6标准，在不同的温度下对有不同夹层材料的玻璃分别进行测试。

关键词：合规管理、设计过程、幕墙、夹层材料、夹层安全玻璃、生命安全

Introduction

Laminated glass is commonly used for applications involving a potential risk of injury to humans. A typical laminated glass construction consists of two or more glass panes bonded together by an interlayer such as Standard PVB, Ionoplast Interlayer (SentryGlas®), Stiff PVB or EVA. Laminated glass has become a major interest in structural applications after the adoption of "Effective Thickness Method by ASTM E 1300" in 2009. Now, more and more structural and façade engineers are becoming aware of the viscoelastic behavior of the interlayers. Thus, now they are considering temperature and load duration as one of the important factors which influence the structural performance of the laminated glass construction. FEM technique based software like SJ Mepla can model the laminated glass as a composite material by incorporating the time and temperature dependent properties of the interlayers. This allows the engineers to differentiate between the structural performances of laminates with various

简介

夹层玻璃通常被用于涉及对人员有潜在伤害风险的应用中。典型的夹层玻璃结构由两片或更多的玻璃通过常规PVB中间膜、离子性中间膜（SentryGlas）、硬质PVB中间膜或EVA中间膜粘接在一起组合而成。ASTM E1300-2009等效厚度计算方法实施后，结构性应用中已热衷于使用夹层玻璃。现在越来越多的结构和幕墙工程师开始意识到中间膜的粘弹性性能。因此，现在他们正考虑将温度和荷载作用时间作为一个重要的因素；他们会影响夹层玻璃结构的结构性性能。基于如SJ MEPLA的有限元分析技术软件可以将夹层玻璃模拟成包含与中间膜相关的时间和温度特性的复合材料。这将可以让工程师们区分使用不同类型中间膜的夹层玻璃的结构性性能。然而针对玻璃破碎后强度，他们仍然必须依靠破碎性测试方法。破碎后强度是一些复杂因素的结果，到目前为止很难被模型化分析。已经有尝试通过采光顶破坏性冲击测试来对比夹层玻璃面板定性的剩余强度。

Figure 1. Greenhouse project overhead glass application using Laminated Safety Glass (Source: Ingo Stelzer)
图1. 温室使用夹层安全玻璃的采光顶应用（来源：Ingo Stelzer）

types of interlayers. However, for post breakage strength, they still have to rely on destructive strength testing methods. Post breakage strength is a result of some complex parameters which are hard to model analytically so far. An attempt has been made to compare the qualitative residual strengths of laminated glass panels through destructive impact testing for a canopy application.

Laminated glass has a significant improvement in the post breakage strength over a monolithic layer of glass, the glass fragments adhere to the interlayers so that a certain remaining structural capacity is obtained as the glass fragments "arch" or lock in place. This capacity depends on the fragmentation of the glass and increases with increasing fragment size. Therefore, laminated glass elements achieve a particularly high remaining structural capacity when made from annealed or heat strengthened glass that breaks into large fragments. The post breakage behavior further depends on the interlayer material. The most common interlayer is PVB, whose mechanical properties are heavily depended on temperature and load duration. At room temperature, PVB is soft with an elongation at break of more than 250%. For higher temperatures and load durations, the shear transfer is greatly affected. Low stiffness of the PVB interlayer results in "Blanket Effect" (see Figure 1) as soon as the glass breaks even for vertical applications because of the self-weight of the panel especially with large panel sizes and minimal supports. SentryGlas® Ionoplast Interlayer, from Kuraray (originally invented by DuPont), was developed with the aim of achieving higher stiffness, temperature resistance, resistance to tearing in point fixed rotule applications. This helps in achieving a superior post breakage strength and design redundancy (Figure 1, 2).

相对于单层玻璃，夹层玻璃在玻璃破碎后强度上已经有了显著改善；通过玻璃碎片粘接在中间膜上以致于夹层玻璃会获得一定的剩余结构性性能。此能力取决于玻璃碎片状况，并随碎片大小的增大而增强。因此当夹层玻璃由能产生较大碎片的浮法或半钢化玻璃制成时，夹层玻璃能达到一个特别高的剩余结构性性能。此外，玻璃破碎后性能还取决于夹层玻璃中间膜。最常见的中间膜是其力学性能非常依赖于温度和荷载作用时间的PVB中间膜。在室温下，具有超过250%延伸率的PVB中间膜是软的。对于更高的温度和荷载作用时间，PVB中间膜的剪切传递会受到极大的影响。尤其是因为大尺寸和最少支撑的玻璃面板的自身重量，即使在立面玻璃应用中玻璃一经破坏，PVB中间膜的低硬度会导致“覆盖效应（图1）”。来自可乐丽公司的SentryGlas离子性中间膜（由杜邦公司发明）为实现更高硬度、耐高温和在点式安装中耐撕裂的目标被开发出来。这将有助于实现卓越的玻璃破碎后强度和设计自由度。表1是PVB中间膜和SentryGlas离子性中间膜的力学性能对比（图1、2）。

上表给出了常规PVB中间膜和SentryGlas离子性中间膜力学性能对比。玻璃破碎后强度受玻璃层破坏形式、支撑条件和温度显著地影响。即使是同一类型的玻璃，玻璃的破碎形式都是一个大的变量；这使得玻璃的破碎后强度分析建模成为几乎不可能完成的任务。因此，工程师们必须依靠破坏性测试。玻璃破碎后强度可被如下分类：

针对采光顶玻璃结构破碎后强度的规范要求

对允许维修和清洁活动的如框架和点式支撑的各种采光顶玻璃结构，DIN 18008-6规范和之前的GS屋面玻璃指南（维修工人在屋顶上）是有效的。

在德国，允许维修和清洁工的采光顶玻璃必须测试玻璃破碎后强度。冲击物是标准化的50公斤重的软质冲击物。冲击测试后，试样必须承受1.0KN的单一荷载；荷

Interlayer Type 中间膜类型	Density 密度	Young's Modulus @ 50°C, for 1 hour load 杨氏模量（50° C，1小时荷载）	Poisson Ratio 泊松比	Coefficient of Thermal Expansion 热膨胀系数	Tensile Strength 抗拉强度
Ionoplast (SentryGlas®) 离子性中间膜 (SentryGlas)	850 Kg/m2 850 公斤/立方米	12.6 MPa 12.6 兆帕	0.5	12.5 x 10-5 / °C	34.5 MPa 34.5 兆帕
Standard PVB (Butacite®) 常规PVB（Butacite）	1070 Kg/m3 1070 公斤/立方米	0.16 MPa 0.16 兆帕	0.5	2.2 x 10-4 /°C	20 MPa 20 兆帕
Stiff PVB (Trosifol® EXTRA STRONG) 硬质PVB（Trosifol EXTRA STRONG）	1081 Kg/m3 1081公斤/立方米	1.20 MPa 1.20 兆帕	0.5	1.6 x 10-4 / °C	32 MPa 32 兆帕

Figure 2. Comparison of Mechanical Properties of SentryGlas® and Standard PVB (Source: Stelzer / Rooprai)
图2. 常规PVB中间膜和SentryGlas®离子性中间膜力学性能对比（来源：Stelzer / Rooprai）

Figure 2 gives a comparison of the mechanical properties of SentryGlas® Ionoplast and Standard PVB interlayers. Post breakage strength is significantly affected by the breakage pattern of the glass layers, support conditions, and temperature. Breakage patterns of glass can be a big variable even for the same type of glass and this makes analytical modeling of its post breakage strength a near-impossible task. Thus, engineers have to rely on destructive testing for this. Post breakage strength can be categorized as follows.

Code Requirements for Post Breakage Strength for Overhead Glazing Constructions

The pr DIN 18008-6 Standard and former GS Roof Glazing Guidelines (for maintenance workers on the roof) are valid for different overhead glazing constructions, like framed or point supported designs, when access for maintenance or cleaning activities will be allowed.

In Germany, the overhead glazing that is accessible for maintenance and cleaning should be tested for post breakage strength. The impact body is a standardized soft body impactor weighing 50Kg. After impact testing, the specimen has to be loaded with a single load of 1.0KN, applied to an area of 200 x 200mm. This should represent a single person standing on the glass surface. After breakage of the uppermost glass sheet, the whole glazing element must stay on its supports for at least 30 minutes. After this, the impact body must be dropped from a height of 900mm and has to hit the specimen on locations that cause maximum glass and support damage. The test is successful if the specimen does not slide from the supports, the impact does not penetrate the laminated glass and no dangerous glass fragments fall down.

Testing carried out:

1. Immediate Post Breakage Strength against "fall through"
2. Medium Duration Post Breakage Strength Testing (More than 30 mins. as per prDIN 18008 – 61)

Separate tests were conducted for both above types of strengths and same have been presented in this paper.

Structural Glass Analysis pre Breakage

Structural performance of laminated glass in frameless point-supported overhead canopy applications is very critical because of high stress concentrations at the fixing points. In these applications, glass elements are held in position to sustain the imposed load without any structural framework running along the edges. Instead, the panels have metal patch plates or point fixings called rotules or spider fittings.

In these types of applications, the flexural behavior of the panel is very different from the one for a framed glass panel as large stress concentrations are observed around the rotule fixings. Structural analysis for one such application was performed in SJ Mepla software.

Table 2 gives a comparison of structural performance results in terms of induced deflections and stress levels in a 1194mm x 1500mm glass panel subjected to a point load of 50Kg for a duration of 1 hour. The analysis has been performed on following glass constructions:

a) 6mm Tempered + 0.89 SentryGlas® Ionoplast + 6mm Tempered

b) 6mm Tempered + 1.52 Standard PVB + 6mm Tempered

c) 12mm Monolithic Tempered Glass (Control Sample)

A control sample of 12mm monolithic tempered glass panel was analyzed for comparing the extent of coupling provided by the interlayers. Table 2 gives the numbers for deflection and stresses in the panel for the same load and boundary conditions.

Laminated safety glass produced with high strength, high stiffness Kuraray interlayers is considerably lighter than laminates produced with standard polyvinyl butyral (PVB), as the comparison shows. The SentryGlas® Ionoplast interlayer is approximately 100 times stiffer and five times stronger than Standard PVB; the transmission of load between the two sheets of glass in the laminate is almost perfect, leading to a rate of deflection that is less than half of that achieved by laminates using PVB of the same construction. Consequently, the laminate can either be used to bear greater loads or – as in the case above – reduced in thickness and weight without compromising (Figure 3).

载需被加载在200*200毫米范围内。该荷载加载等同于一个人站在玻璃结构表面。当最上面一层玻璃破碎后，整个玻璃构件必须保持至少30分钟的支撑。此外，冲击物必须从900毫米高度下落并撞击能造成玻璃和支撑最大限度破坏的位置。如果玻璃试样没有从支撑结构中滑落，冲击物没有穿透夹层玻璃和没有危险的玻璃碎片掉落，测试是成功的。

测试实施：

1.即时的抗“坠落”玻璃破碎后强度

2.中等时间长度的破碎后强度测试（DIN 18008-6，超过30分钟）

对如上两种类型的强度进行了分别测试，并都在本报告中体现。

破碎前结构性玻璃分析

由于在支撑点的高的应力集中，因此在采光顶雨棚应用中的无框架点式支撑的夹层玻璃的结构性性能是非常重要的。在如上应用中，玻璃构件被安装在边缘没有任何结构性支撑的结构上用以支撑所加荷载。玻璃面板只有金属点状扣件或被称为驳接爪的点式支撑。

在这些应用类型中，由于在点式构件周围会产生大的应力集中，玻璃面板的抗弯性能是不用于框架支撑玻璃面板的，。一个这种应用的结构性分析在SJ MEPLAS软件中被模拟。

表2给出了尺寸为1194mm*1500mm，在50公斤点式荷载持续作用1小时条件下的玻璃面板的变形和应力对比。对如下玻璃结构进行分析：

a）6mm钢化玻璃+0.89mm SentryGlas离子性中间膜+6mm钢化玻璃

b）6mm钢化玻璃+1.52mm常规PVB中间膜+6mm钢化玻璃

c）12mm单层钢化玻璃（对比样本）

12mm单层钢化玻璃对比样本用来对由中间膜带来的玻璃间连接程度对比分析。表2给出了玻璃面板在同样荷载和支撑条件下的变形和应力数值。

从对比中可以看出，使用可乐丽高强度和高硬度制作的夹层安全玻璃相比使用常规聚乙烯醇缩丁醛（PVB）制作的夹层安全玻璃可大大减轻玻璃重量。SentryGlas离子性中间膜是常规PVB中间膜硬度的100倍和抗撕裂强度的5倍，在夹层玻璃

Laminated Glass Construction 夹层玻璃结构	Stress 应力	Deflection 变形
6mm FT-Glass+ 0.89 SentryGlas® Ionoplast + 6mm FT-Glass 6毫米 浮法玻璃+ 0.89 SentryGlas® 离子性中间膜+ 6毫米 浮法玻璃	66.47 MPa 66.47 兆帕	14.68mm 14.68毫米
6mm FT-Glass+ 1.52 Standard PVB + 6mm FT-Glass 6毫米 浮法玻璃+ 1.52 常规PVB + 6毫米 浮法玻璃	154.67 MPa 154.67 兆帕	28.74 mm 28.74 毫米
12 mm Monolithic FT-Glass 12 毫米 单片钢化玻璃	64.62 MPa 64.62 兆帕	14.93 mm 14.93 毫米

Figure 3. Structural Calculation Results (Source: Stelzer / Rooprai)
图3. 结构计算结果（来源：Stelzer / Rooprai）

Above results conclude that even at an elevated temperature range of 50ºC, SentryGlas® Ionoplast interlayer provides an efficient coupling to the glass layers to match its structural performance with an equivalent monolithic glass whereas PVB interlayer because of inefficient coupling lags behind in structural performance as both stresses and deflections in PVB laminates are around 100% more than those in SentryGlas® Ionoplast laminates.

In order to remain within the deformation limits, the laminated glass panels with Standard PVB would have had to have been considerably thicker than those made with the SentryGlas® Ionoplast interlayer. Their weight would also have been correspondingly higher. In order to ensure required safety levels, a much more substantial supporting structure would have been required than the intended light-dimensioned point fixing system designed for the glazing. The use of such a structure would have spoilt the desired transparent effect of the glazing, particularly when illuminated from above. Following intensive laboratory testing, which confirmed the FEM calculations of the simulation by physical strength testing.

Immediate Post Breakage Structural Performance through Impact Testing

Impact tests were done at Intertek ATI Inc. York, Pennsylvania by dropping a soft bag weighing 100Kgs (typical weight of a maintenance worker along with his tools and tackles) from a height of 1.20m at a test temperature of 50ºC. The test method simulates potential loading from installation and/or maintenance workers in distress. The panels were conditioned at 50°C for 1 hour before the test. The test set up was enclosed with insulated panels to ensure there is no variation in test results due to temperature. The insulated panels were removed just before the impact.

Laminates made from SentryGlas® Ionoplast interlayer provided a barrier against the impactor. The impactor was removed after 15 minutes without any tearing of interlayer observed at the rotules. Whereas laminates made from EVA, Standard PVB and Stiff PVB collapsed as soon as the impactor struck, and failed to act as a barrier.

The Next level of test programs shall be aimed at knowing the minimum interlayer thickness that is required for glass panels to pass the post breakage strength requirements set by the standards with temperature as the key variable factor.

Post Breakage Strength Testing (30 Minutes or More)

German Standard pr DIN 18008 – 61, (Glass in Buildings – Design & Construction Rules – Additional requirements for walk-on glazings in case of maintenance procedures) in February 2015, sets new guidelines for post breakage performance. The new regulation requires a laminated glass construction to sustain the weight of 100Kg for at least 30 minutes after breakage of the top layer of glass. First, the panel is subjected to an impact made by dropping a twin tyre impactor, which weights 50Kg, from a height of 900mm. This is followed by imposing a load of 100Kg for 30 minutes on an area of 200mm x 200mm. After the breakage of the uppermost glass layer, the whole glazing element must stay on its supports for at least 30 minutes. The test is successful if the specimen does not slide from the supports, the impact does not penetrate the laminated glass and no dangerous glass fragments fall down.

Testing

Post breakage strength tests on point supported glass panels (1500mm x 2000mm) for a typical canopy application were conducted at University of Armed Forces in Munich, Germany.4 Nine glass panels each with 4 different interlayers: SentryGlas® Ionomer (1.52 & 0.89mm), Stiff PVB (1.52mm), and Standard PVB (1.52mm) were prepared for testing at 3 different temperature scenarios (Figure 4).

的两层玻璃板间荷载传递接近完美，会使得在同样荷载条件下玻璃变形小于使用相同结构的PVB夹层玻璃的变形的一半（图3）。

如上结果显示即使在50摄氏度高温条件下，SentryGlas离子性中间膜也能提供玻璃间有效的连接从而使其夹层玻璃的结构性能相同于同等厚度的单层玻璃结构；反之由于PVB中间膜在结构性能上的无效连接，PVB夹层玻璃的应力和变形会高于SentryGlas夹层玻璃一倍。

为保持玻璃结构在变形极限内，常规PVB夹层玻璃面板必须大大厚于使用SentryGlas离子性中间膜的夹层玻璃。它们的重量也相应的更重。为保证所要求的安全水平，相对于预期的少遮挡的点式支撑系统，将需要一个更大的支撑构件将。这种结构的使用会破坏预期的透明效果，尤其是当有灯光照射的情况下。经过大量的实验室测试，模拟的有限元计算方法通过物理强度测试获得确认。

由冲击测试带来的即时破碎后结构性表现

在宾夕法尼亚州Intertek ATI Inc. York进行了冲击试验，该实验是在测试温度为50摄氏度下，从1.20米的高度落下一个100公斤重的软袋（这是典型的一个维修工人带上他的工具和装备一起的重量）。测试方法模拟安装和（或者）维修工人遇险后潜在的荷载。测试开始前玻璃面板会在50摄氏度下保持一个小时。用隔热面板把测试装置围起来以确保测试结果不会因为温度变化而波动。隔热面板仅在冲击测试前移走。

用SentryGlas离子性中间膜做的夹层玻璃在冲击后就像一道屏障挡住了冲击物。15分钟后移走冲击物发现在支撑节点上中间膜没有任何的撕裂。然而，用EVA，常规PVB和硬质PVB中间膜做的夹层玻璃在冲击后马上坍塌，并不能做为一个屏障支撑冲击物。

下一个测试项目将致力于了解将温度作为关键可变因素的规范设定的玻璃面板通过破碎后强度要求的最小中间膜厚度。

破碎后强度测试（30分钟或更多）

2015年2月的德国标准DIN 18008–61（建筑中的玻璃–设计和建设规则–如果维修时需要在玻璃上行走的附加要求）已经在之前有要求破碎后性能。新规范要求在夹层玻璃的上片玻璃破碎后其结构可以支撑100公斤至少30分钟。首先，玻璃面板会遭受两次冲击物冲击；先是50公斤冲击物从900毫米高落下，接着是在200 x 200

Dimension of the Specimen: 1.500 mm x 2.000 mm **样品规格:** 1.500 毫米 x 2.000 毫米			
Supports: PAULI & SOHN Rotule System 751260 VAM M16 (not fully motion restricted) **支撑:** PAULI & SOHN 点式系统 751260 VAM M16（不完全活动限制）			
Laminate Construction 1. **夹层玻璃结构1**	**Laminate Construction 2.** **夹层玻璃结构2**	**Laminate Construction 3.** **夹层玻璃结构3**	**Laminate Construction 4.** **夹层玻璃结构4**
2 x 6 mm FT-Glass 2 层 6 毫米浮法玻璃	2 x 6 mm FT-Glass 2 层 6 毫米浮法玻璃	2 x 6 mm FT-Glass 2 层 6 毫米浮法玻璃	2 x 6 mm FT-Glass 2 层 6 毫米浮法玻璃
1.52 mm Interlayer 1.52 毫米中间膜	1.52 mm Interlayer 1.52 毫米中间膜	0.89 mm Interlayer 0.89 毫米中间膜	1.52 mm Interlayer 1.52 毫米中间膜
Butacite® PVB Butacite PVB	Trosifol® EXTRA STRONG Trosifol超强PVB	SentryGlas® Ionoplast SentryGlas 离子性中间膜	SentryGlas® Ionoplast SentryGlas 离子性中间膜
“Standard PVB” “常规PVB”	“Stiff PVB” “硬质PVB”	“Ionoplast” “离子性中间膜”	“Ionoplast” “离子性中间膜”

Figure 4. Glazing Constructions (Source: Stelzer / Rooprai)
图4. 玻璃结构（来源：Stelzer / Rooprai）

The objective was to know which interlayer-type laminate construction can pass the requirements set by pr DIN 18008-6 at three different temperatures (-20°C, +21°C and +50°C). Three panels were tested for each temperature scenario. As a soft-body impactor, the EN 12600 Pendulum Test “Double-Tire“ impactor was used in a vertical position. An attempt was made to know the ultimate capacity of the laminates. However, the test apparatus had a limitation of applying a maximum load of 400Kg. The laminates were conditioned for at least 3 hours for each temperature scenario. The test chamber had a temperature control mechanism (AC-System) for a temperature range of -25°C to +50°C. The laminate construction with all different types of interlayers was strong enough to withstand the impact against any breakage. Therefore the upper layer of laminates in each case had to be broken manually with a center punch. It was followed by placing a 100Kg concrete block on the glass panel for 30 minutes. The test was aimed to know the ultimate post breakage performance limit so load was ramped up to 400Kg in increments of 100Kg, with a 15-minute time interval between each load increment. Laminates with SentryGlas® Ionoplast and Stiff PVB interlayers sustained this load of 400Kg without collapse at -20°C and + 21°C temperatures (See Figure 2). Whereas in Figure 3, Standard PVB laminate could not sustain the 100Kg imposed load at +21°C, as it collapsed in few seconds when the load was placed due to tearing of the interlayer at the rotules (Figure 5, 6 & 7)

At an elevated temperature of 50°C, broken laminate construction with Standard PVB & Stiff PVB interlayers could not sustain their own self weight as they collapsed (See Figures 4 and 5) soon after breakage of both layers. Whereas, the laminate construction made with 0.89mm SentryGlas® Ionoplast interlayer sustained a weight of 100Kg for more than 30 minutes and collapsed when load was ramped up to 200Kg. Similarly, 1.52mm Ionomer laminate could sustain a load of 200Kg for more than 30 minutes after breakage and collapsed when load was ramped up to 300Kg.

Deflection Measurements for Estimating Modulus of Broken Laminate

Deflection measurements were made during the test for all three temperature scenarios to make an estimate of the post glass breakage strength of the laminate constructions. At –20°C, the 1.52mm Ionomer laminate demonstrated the lowest deflection after 30 minutes (See Figure 6), whilst at +21°C both SentryGlas® Ionoplast laminates (1.52 and 0.89mm) outperformed the PVB laminates (Figure 8, 9, 10).

毫米面积上加载100公斤荷载30分钟。在最上层玻璃破碎后，整个玻璃构件必须保持在其支撑系统上至少30分钟。如果玻璃试样没有从支撑结构中滑落，冲击物没有穿透夹层玻璃和没有危险的玻璃碎片掉落，测试是成功的。

测试

在德国慕尼黑武装部队大学4进行了典型雨棚应用中点支撑玻璃面板的破碎后强度测试。用4种中间膜，即SentryGlas离子性中间膜（1.52和0.89毫米厚），硬质PVB（1.52毫米厚），常规PVB(1.52毫米厚)，做夹层玻璃，每种中间膜做9片玻璃样片用于三种不同温度下的测试（图4）。

测试的目的是了解在三种不同温度下（–20°C，+21°C和+50°C）哪一种中间膜所做夹层玻璃结构能通过DIN 18008–6设定的要求。每一种温度将测试3片玻璃样片。在EN 12600摆锤试验的软体冲击物将在新的垂直方向使用，尝试了解夹层玻璃的最大能力。然而，测试装置有一个限制，只能装载400公斤的最大重量。夹层玻璃样片在每种温度下将保持至少3个小时。在测试室内有一个温度控制装置（AC–System），它可以控制温度从–25°C到+50°C。使用各种不同的中间膜的夹层玻璃结构强度很大并可以承受冲击以防破碎。因而，在每个测试中都需要用中心冲头手动将上层玻璃打碎，紧接着在玻璃样片上放置100公斤混凝土块30分钟。测试主要是了解极限的破碎后性能，所以荷载以每15分钟100公斤的增量加大到400公斤。在–20°C和+21°C下，SentryGlas离子性中间膜和硬质PVB中间膜夹层玻璃可以支撑400公斤荷载而没有坍塌（图2）。 然而在图3，当玻璃破碎后荷载加载到样片时，由于在支撑节点的中间膜被撕裂了，夹层玻璃几秒钟之内就坍塌了。因此，常规PVB夹层玻璃在+21°C下不能支撑所加100公斤荷载（图5–7）。

在温度提升到50°C，当常规PVB和硬质PVB夹层玻璃破碎后，它们不能支撑它们本身的玻璃自重，因为它们的两片玻璃破

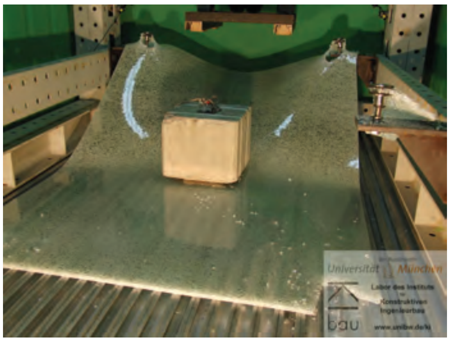

Figure 5. Collapsed Standard PVB laminate with 100Kg at +21°C (Source: UNIVERSITÄT der Bundeswehr, München)
图5. +21°C下，100公斤荷载常规PVB夹层玻璃坍塌（来源：UNIVERSITÄT der Bundeswehr, München）

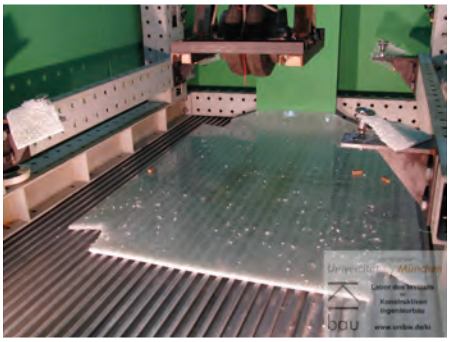

Figure 6. Broken Standard PVB laminate collapsed at +50°C (Source: UNIVERSITÄT der Bundeswehr, München)
图6. +50°C下，破碎的常规PVB夹层玻璃坍塌（来源：UNIVERSITÄT der Bundeswehr, München）

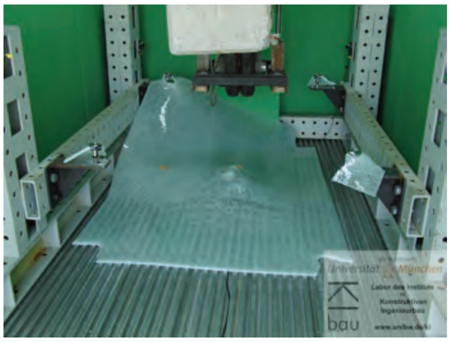

Figure 7. Broken Stiff PVB laminate collapsed at +50°C (Source: UNIVERSITÄT der Bundeswehr, München)
图7. +50°C下，破碎的硬质PVB夹层玻璃坍塌（来源：UNIVERSITÄT der Bundeswehr, München）

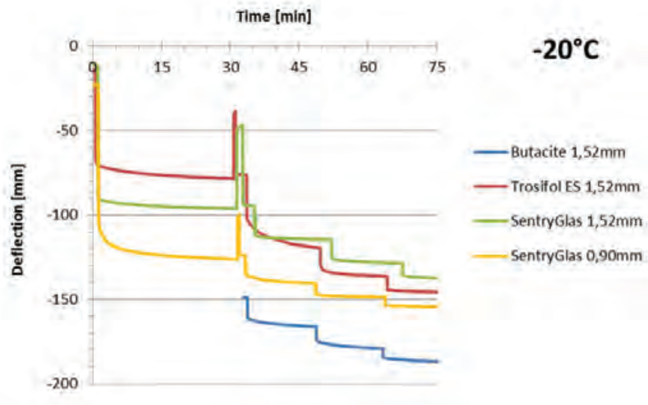

Figure 8. Deflection vs Time Measurements @ -20°C
Butacite® = Standard PVB, Trosifol® ES = Stiff PVB, SentryGlas® = Ionoplast (Source: UNIVERSITÄT der Bundeswehr, München)
图8. –20° C下，变形量 vs 时间（来源：UNIVERSITÄT der Bundeswehr, München）

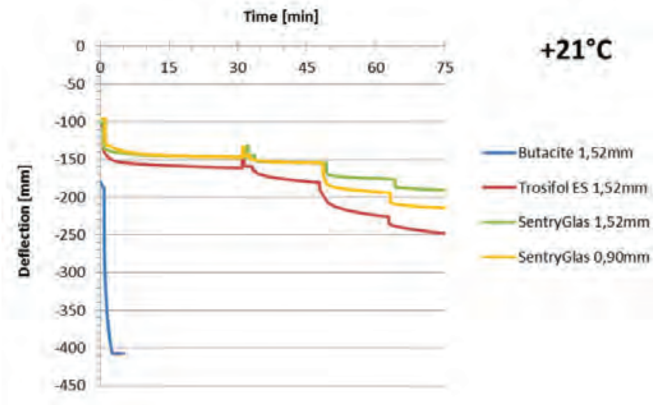

Figure 9. Deflection vs Time Measurements @ +20°C
Butacite® = Standard PVB, Trosifol® ES = Stiff PVB, SentryGlas® = Ionoplast (Source: UNIVERSITÄT der Bundeswehr, München)
图9. +20° C下，变形量 vs 时间（来源：UNIVERSITÄT der Bundeswehr, München）

Conclusions

1. At -20°C, laminates made from the 4 interlayer candidates, i.e., 0.89mm SentryGlas® Ionoplast, 1.52mm SentryGlas® Ionoplast, 1.52mm Standard PVB, and 1.52 Stiff PVB pass the post breakage strength requirements of the new German Standard pr DIN 18008 – 6.

2. At -20°C, all 4 candidates had their ultimate strength more than 400Kg as there was no collapse of the panel due to tearing of the interlayer at rotules.

3. At +21°C, SentryGlas® Ionoplast and Stiff PVB laminates pass the post breakage strength requirements of DIN 18008 – 6, but the Standard PVB laminate does not (for this type of construction).

4. At +21°C, 0.89mm & 1.52mm, SentryGlas® Ionoplast laminate had almost similar post breakage strength till about 45 minutes from the breakage.

5. For tropical climate regions where the ambient temperature is more than +45°C, SentryGlas® Ionoplast interlayer laminates meet and exceed the requirements of pr DIN 18008- 6 Standard as the only interlayer material.

Please note that the findings are valid for point-fixed fully tempered glass and the described testing set-ups only. Glazing construction using heat strengthened glass, annealed glass and/or different fixations systems could produce different performance. Further testing and research will be conducted to get a better understanding of the post glass breakage behavior of laminated glass and to develop appropriate design methods.

Modern construction without laminated glass is no longer an option to meet architect and specifier needs, while also meeting international codes and regulations. At the same time, global challenges in the industrial world are calling for new glazing solutions. Interlayer suppliers have been able to address some of these challenges through innovative products and will continue to do so in the coming years.

More recently, new requirements have added challenges to the performance of laminated glass:

- UV filtration performance
- Acoustic performance
- Larger glass panes and minimally supported glass
- Post breakage performance
- Enhanced glazing system performance for:
  - o Blast and ballistic resistance
  - o Very high wind load and debris resistance for hurricane-sensitive areas
- Concerns about the safety performance of tempered glass
- Durability and performance in open edge and silicone sealed applications
- Changes in color and transparency/ translucency
- Material inclusion and combination with glass coatings

Laminated glass is also increasingly challenged to help meet the energy control requirements imposed on new and retrofitted

Figure 10. Test set-up before impact, installed in a climate chamber (Source: UNIVERSITÄT der Bundeswehr, München)
图10. 冲击前的测试装置安装于气候室（来源：UNIVERSITÄT der Bundeswehr, München）

碎后，它们迅速坍塌了（图4和图5）。然而，0.89毫米SentryGlas夹层玻璃结构破碎后却能支撑100公斤荷载超过30分钟，而后当荷载加大到200公斤后坍塌。相类似的，1.52毫米SentryGlas夹层玻璃破碎后可以支撑200公斤荷载超过30分钟，而后当荷载加大到300公斤时坍塌。

预估破碎夹层玻璃模量的变形测量

在测试中进行了所有三种温度下的变形测量，以此预估夹层玻璃结构破碎后的强度。在–20 ° C下，1.52毫米离子性中间膜破碎后30分钟的变形量最小（图6）。同时，在+21° C下，1.52毫米和0.89毫米的SentryGlas离子性中间膜夹层玻璃的变形量都胜过PVB夹层玻璃（图8–10）。

结论

1. 在–20° C下，4种中间膜，即SentryGlas离子性中间膜（1.52和0.89毫米厚），硬质PVB（1.52毫米厚），常规PVB(1.52毫米厚)，做的夹层玻璃通过了德国规范DIN 18008–6的破碎后强度要求。

buildings. These requirements have led to a dramatic increase of interlayer solutions. At the beginning, some of these challenges were met through modification of the original "automotive" PVB: Interlayer thickness ranging from 0.38mm up to 4.56mm or more, sheet size increases and the introduction of colors for architectural applications, including translucency. However, as the architectural laminated glass market was maturing, the original PVB recipe proved to have its limitations for architectural applications. This led to the modification of the PVB recipe for applications such as enhanced acoustics, and the development of other polymers such as SentryGlas® Ionoplast and EVA.

This summary illustrates that the use of advanced interlayer, thanks to their stiffness and retained transparency – even after many years of use – presents new opportunities for architects and engineers to carry out cost-effective modernization projects and innovatively adopt laminated safety glass in construction. Such glass is already being used on a large scale for architectural projects such as glazed balustrades, floorings, staircases and pedestrian bridges – bringing with it additional benefits in terms of the preservation of valuable resources.

2. 在−20° C下，所有四种中间膜做的夹层玻璃都有超过400公斤的最大破碎后强度，玻璃样片没有因为在支撑节点的中间膜撕裂而坍塌。

3. 在+21° C下，SentryGlas和硬质PVB夹层玻璃都通过了DIN 18008−6的破碎后强度要求，但常规PVB夹层玻璃没能通过（对于这种类型的结构）。

4. 在+21° C下，0.89毫米和1.52毫米SentryGlas夹层玻璃的破碎后强度几乎相同，都达到了破碎后支撑45分钟。

5. 对于环境温度超过+45° C的热带地区，SentryGlas作为唯一一种中间层材料，其夹层玻璃满足和超过DIN 18008−6的破碎后强度要求。

请注意这些发现仅对点式支撑的全钢化玻璃和上文描述的试验设定有效。使用半钢化玻璃，浮法玻璃和（或者）不同固定系统的玻璃结构可能会有不同的性能表现。为了更好的理解夹层玻璃的破碎后的表现和得到合理的设计方法，需要进一步测试和研究。

没有夹层玻璃的现代玻璃结构不再能满足建筑师和设计者的要求，同时也不能满足相应的规范和标准要求。接下来玻璃行业面对的全球挑战是希望有新的玻璃解决方案。中间膜供应商通过创新的产品可以消除一部份挑战并还会在今后几年继续去创新。

最近以来，新要求给夹层玻璃性能增加了挑战：

- 紫外线透过性能
- 隔音性能
- 更大玻璃版面和最小支撑体系
- 破碎后性能
- 提升玻璃体系性能，如：
  - o 防爆炸和防弹
  - o 飓风多发地区的防高风压和碎片冲击
- 钢化玻璃安全性能的担忧
- 开边设计和硅胶密封应用中的耐久性能
- 颜色和透明/半透明的改变
- 包含和与玻璃涂层结合的材料

对于新建和改建翻新的建筑物，夹层玻璃正受到越来越多关于满足节能要求的挑战。这些要求导致了更多中间膜解决方案的产生。刚开始，通过改良最初的“汽车”PVB可以满足这些挑战的一部分要求，比如中间膜的厚度从0.38mm到4.56mm甚至更厚，增大胶片的尺寸，在建筑应用中引入包括半透明在内的彩色方案。然而，随着建筑夹层玻璃市场的成熟，最初的PVB配方在建筑应用中是有局限性的。这导致了PVB配方的改良，如提高隔音性能的应用，发展包括离子性和EVA其它聚合物。

总结表明先进中间膜的使用（感谢他们的硬度和透明度，甚至在使用多年后依然保持），给建筑师和工程师带来了在建设中执行有成本效益的现代化项目和创新性地采用夹层安全玻璃的新的机会。这些玻璃已经在诸如玻璃栏杆，地板，楼梯和行人天桥等建筑项目上大量使用了并带来对于珍贵资源保护的额外好处。

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