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A laminated glass wall will protect Warnemünde from high water

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Warnemünde is a former fishing village on the Baltic coast, now part of the city of Rostock. A new flood protection wall is due to be built along a river in an architecturally sensitive inner-city area. Transparent or movable solutions are necessary, while the barrier must withstand water, flotsam, ice and the impact of boats of up to two tons weight. Here the optimum solution is a 4-layer laminated glass wall. The article describes the research required to establish realistic impact loads (via transient-dynamic finite element analysis), the safety concept and the applied design criteria for glass sections.

Keywords: flood prevention walls, laminated glass, flotsam and boat impact, transient-dynamic finite element analysis

1. Planning objectives

Flood protection structures at the Baltic Sea are required to protect against wind-induced seasonal flooding rather than tidal floods. The typical flood season is winter. An existing concrete flood protection wall is no longer considered stable or sufficiently high, due to an increase of predicted peak water level. The client brief for the new wall was challenging: The flood barrier must not hinder the current usage of the quay for boat moorings, and must not disturb the view from adjacent houses to the river and vice versa. After a flood warning there is very little time and only a limited workforce available to close temporary openings or to erect mobile walls, and therefore mobile elements must be reduced to a minimum or made fully automatic. All solutions must also function in winter under freezing conditions or after heavy snowfall. There is only a narrow strip of land available for any flood prevention construction between quay and street. The waterfront architecture is of historic interest and must not be spoiled by technical constructions.

2. Feasibility studies, alternatives, comparison

The following solutions have been considered: moving walls (flaps, miter gates, elevating walls) as a permanent mechanical solution; removable walls, which are erected only when a storm flood has been forecast, but with a permanent sub construction and coupling points in the pavement; and, finally, rigid walls. All three solutions have drawbacks: moving walls may fail to work in severe winter conditions, and need plenty of maintenance. The removable walls require more time and many workers for erection. Rigid walls are less complex and require comparatively little maintenance, but can greatly disturb the surrounding architecture and block riverside views if not transparent. Thus, the optimum solution is a combination of all these alternatives: Rigid concrete for the base, rigid-transparent (glass) in the upper part of the wall where transparency matters most, and mobile walls for openings, giving access to moorings and the quay.

Figure 1: Proposed solution with a glass-topped wall, left [2]

3. Optimum solution

The optimum solution for the flood protection wall is an integrated approach which solves both the technical issues and the objectives for maintaining Warnemünde's architectural unity. The technical and optical functions go hand in hand: The glass balustrade protects the historic city against high water, while ensuring an unobstructed view in both directions from the small fishing houses to the water. The wide quay is not only designed for mooring, but also creates a new space for tourists and inhabitants – a pedestrian zone at the water's edge which serves as a small harbour for recreational and fishing boats. The formerly dreary embankment becomes an attractive part of the town. The concrete lower section at the water's edge is constructed as a sheet pile wall. The upper section is a glass-steel-construction, which not only protects against flooding, but also serves as a transparent balustrade for pedestrians. Gates at various stations offer barrier-free access via stairs or ramps to the lower section.

Figure 2: Future view from the river Alter Strom to the storm flood protection wall [2]

The laminated glass wall consists of 4 layers: 2 inner layers of heat-strengthened glass (TVG) and 2 outer layer of fully tempered glass (ESG), with 3 layers of foils in-between. Additional exterior foils create a no-scratch coating. The glass construction is shown in Figure 5. The posts (Figure 3) and the handrail bar (Figure 4) are made of stainless steel, elastically embedded in the concrete construction.

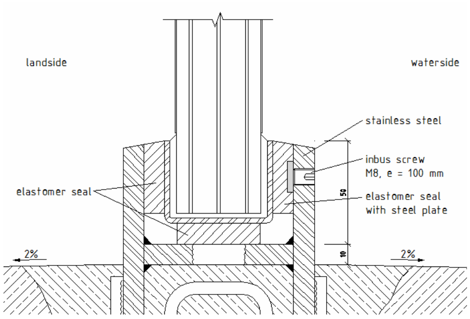

Figure 3: Cross section of lower beam

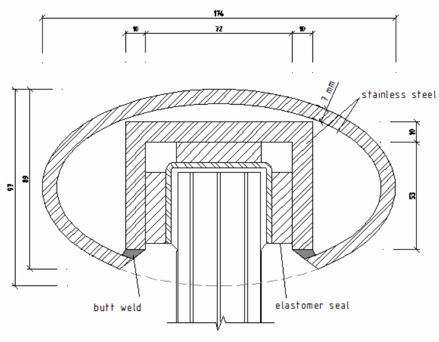

Figure 4: Handrail design

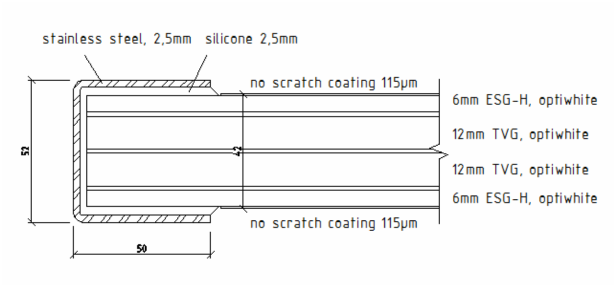

Figure 5: Cross section of laminated glass

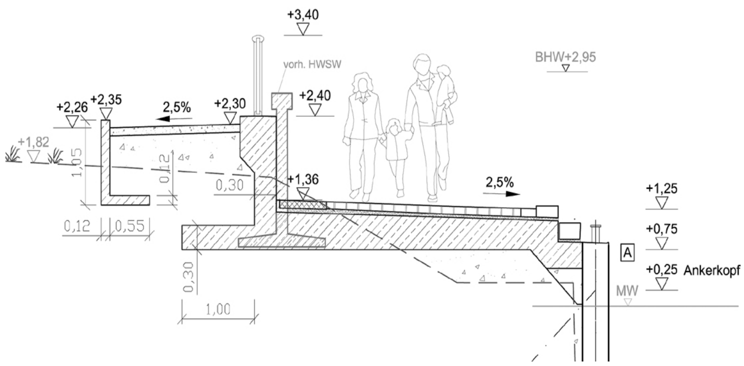

Figure 6: Cross section of flood protection wall as optimum solution, compared with current situation

4. Structural design

4.1. Safety Concept

The proposed wall is one element of a wider storm flood safety scheme for the entire coastline of Mecklenburg-Vorpommern, and for Rostock-Warnemünde in particular [1,2]. A special safety concept was required for the laminated glass wall due to the special fracture behaviour and stability of glass structures. The concept assumes that when any glass section shows signs of distress, such as cracking, the distressed section will remain watertight for sufficient time to allow a temporary stoplog to be installed. A first step was to determine the behaviour of the laminated glass for typical loads (wind, hydrostatic, flotsam as static force) according to codes of practice to ensure the usual level of building safety. In a second step, a probabilistic risk assessment investigated the probability of glass failure under the impact of larger flotsam and abandoned boats, for which no codes of practice exist. This allowed an estimation of the annual costs for glass replacement and the number of stoplogs and workers required to cope with heavy flooding. The proof of water tightness of broken laminated glass is part of the experiment described in Section 5.

4.2. Loads

To calculate the impact loads which the laminated glass walls will have to bear, the effect of insufficiently moored boats striking glass sections was investigated. First, the 100 boats currently moored at the quay were listed and classified. Eight typical categories of boats where modelled in Strand7 FEA-Software to calculate the typical stiffness of the boat hull. The mass was taken from known examples. The average impact velocity and wind loads were calculated using design parameters typical to boat construction.

Table 1: Loads of various boat categories

	Boat category	Stiffness [N/m]	Velocity [m/s]	Mass [kg]
	Heavy boats			
1	with build-up	1.8×10^6 (wood)	2,50	2000
	without build-up		2,00	2000
2	with build-up	3.5×10^7 (steel)	2,50	2000
	without build-up		2,00	2000
3	with build-up	1.0×10^6 (composite)	2,50	2000
	without build-up		2,00	2000
	Lighter boats			
4	with build-up	1.8×10^6 (wood)	2,20	1000
	without build-up		1,70	1000

4.3. Calculation method

The numeric simulation of impact was calculated using an FE-model in Strand7. All elements (glass wall, steel posts and bars) are plate elements. The posts are elastically embedded in the wall's foundation.

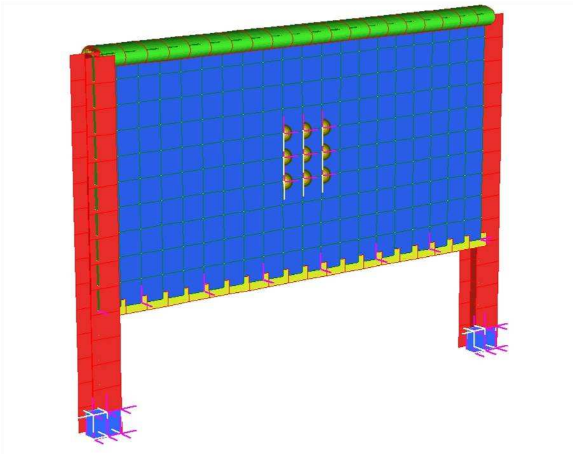

Figure 7: Model laminated glass wall with elastic posts in the ground and handrail as crossbar with Impact 1 situation

The calculations were carried out as a nonlinear transient-dynamic FE analysis for a hard impact. The model has three different impact situations:

- Impact 1: Impact in the centre of the glass section (area 50 cm x 50 cm)
- Impact 2: Impact at the top of the post
- Impact 3: Impact in the middle of handrail (crossbar)

Each impact is analysed under the load of all boot categories 1-4 with and without build-up. The analysis of Impact 1 shows the maximal glass stresses, the Impact 2 and 3 the maximal internal forces in the steel sections.

The following stress limits for impact loads according to TRAV[4], based on [3] and [6], were used to assess the breaking probability of the glass:

$$\sigma_{RD} = 170\ \text{N/mm}^2\ \text{(ESG)}$$
$$\sigma_{RD} = 120\ \text{N/mm}^2\ \text{(TVG)}$$

The 4-layer VSG-glass sections are modelled as isotropic plate elements with full composite effect, acting like a full cross section. This is justified by the extremely short loading time during impact and by the typically low temperatures during winter storm flooding. Wellershoff describes the dependence of G (shear modulus) of the composite interlayer (PVB, SGP) vs. load duration and temperature in [5].

4.4. Conclusion

Glass failure is only associated with impact by a category “boat 2 with build-up”, for which stress limits are exceeded. However, as the number of boats in category “boat 2 with build-up” is limited to 8 % of all boats, there is only a low probability that a wall section will in fact be breached. For all other categories, the loads and corresponding stresses are below critical level and do not result in glass failure. The steel-frame construction resists all kinds of boat impact.

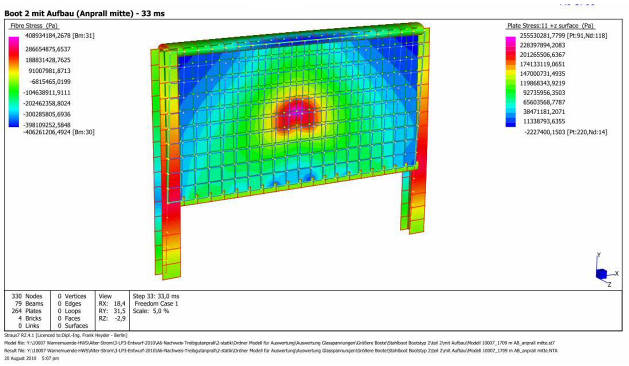

Figure 8: Glass stress from boat impact (category “boat 2 with build-up”)

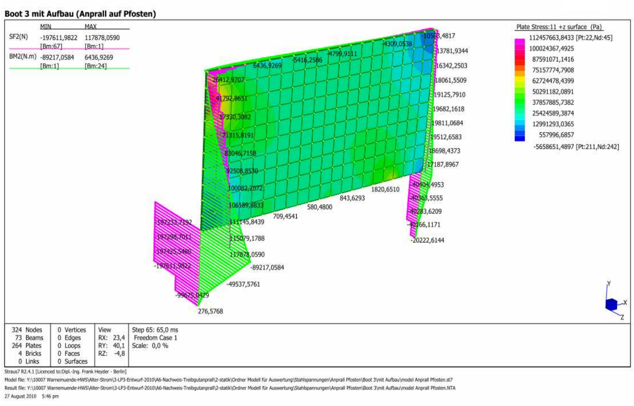

Figure 9: Stress on steel elements from boat impact (category “boat 2 with build-up”)

5. Experimental verification

In an experiment undertaken at Dresden’s Technical University, Prof. Weller’s team investigated the load bearing capacity and the deformation of broken laminated glass sections under hydrostatic water pressure (1.10 m water column to ground-level glass section) resulting from storm flooding. In the experiment, two different composite constructions were investigated, one with PVB foil and the other with SGP interlayers. During the whole experiment duration of 9 hours, no relevant deformation could be detected, and the two composite constructions did not display any differences in terms of deformation [7]. However, in an additional test with a free falling compact mass, the

SGP glass turned out to have a significant better resistance against local penetration than the PVB glass.

Figure 10: Water filling of the specimen [7]

6. Outlook

The project is now fully designed and in its authority approval phase. Detailed design and the tender is planned for 2013. The construction phase is scheduled to run from 2014 to 2016. As the pictures show, the Warnemünde flood protection wall is a highly versatile solution, suitable for many locations worldwide with similar design requirements. Hopefully, the Warnemünde project will become a model for the successful application of laminated glass in flood protection walls in visually sensitive inner-city areas.

Figure 11: Future riverside view [2]

7. Abbreviations

Table 2: Abbreviations

Abbr.	in UK	in USA	in Germany
Float	Float glass	Annealed glass (AN)	Floatglas Spiegelglas
TVG	Heat-strengthened glass	Heat-strengthened glass (HS)	teilvorgespanntes Glas (TVG)
ESG	Toughened glass	Fully tempered glass(FT)	Einscheiben-Sicherheitsglas (ESG)
ESG-H	toughened glass with heat-soak test	fully tempered glass with heat soak test	Einscheiben-Sicherheitsglas mit Heißlagerungstest
PVB	Polyvinyl butyral	Polyvinyl butyral	Polyvinylbutyral
SGP	Sentry glass (plus)	Sentry glass (plus)	Sentry glas (plus)
TRAV			see reference [4]
Strand7	Finite Element Software package		

8. Acknowledgements

The project's client, the Staatliche Amt für Landwirtschaft und Umwelt Mittleres Mecklenburg, Dezernatsgruppe Küste, was fully confident that the glass wall would prove to be the right solution for the project, long before the laboratory tests had been carried out by TU Dresden, Institut für Baukonstruktionen. The authors are grateful to both these institutes for their confidence and professional advice.

9. References

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