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Heiselberg, Per Kvols

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Structures that Include a Semi-Outdoor Space
Part 1: Energy Performance

K. Foteinaki*, C. Papachristou, O.B. Kazanci, B.W. Olesen

International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, Nils Koppels Alle, Building 402, Kgs. Lyngby, Denmark

*kyfote@byg.dtu.dk

Abstract

There are several examples of buildings that are partially or entirely covered by a transparent shield, such that a semi-outdoor space between the building and the shield is created. The purpose of the present study was to investigate the impact of the addition of a shield on the energy use of a building. Two case study buildings were examined; the EMBRACE dwelling, which has a climate shield on two of its sides and the ''Dome of Visions (DoV)'', in which a dwelling is enclosed in a dome-shaped climate shield. Simulations were performed using IDA ICE software, where both buildings were simulated in two versions; with and without their climate shield. The results of the two versions were compared in terms of peak load and energy demand in the Copenhagen region, for three different cases; during the heating season, during the cooling season and during the cooling season with natural ventilation in the semi-outdoor space. In EMBRACE, the heating and cooling demand were only slightly affected by the addition of the climate shield. However, when implementing natural ventilation in the semi-outdoor space both the peak cooling load and the energy demand were reduced during the cooling season by 30.8% and 14.6% respectively. In DoV, the addition of the shield resulted in a reduced heating demand (-37.7%) but significantly higher cooling demand (109.8%), although with natural ventilation the peak cooling load and the energy demand were reduced, by 34.8% and 61.6% respectively, compared to the unshielded version of the building.

Keywords - semi-outdoor space; climate shield; energy demand; peak load

1. Introduction

Semi-outdoor spaces have applications worldwide and cover a wide range of structures, in terms of geometry and materials. There are different perspectives on what could be considered as a semi-outdoor space and could be divided into two general categories. In the first category belong outdoor spaces, which even though they are exposed to outdoor conditions, are moderated to a degree by structures such as transparent roofs or walls protecting them from wind. Semi-covered stadia, bus stations and glass roofs are examples of this category [1,2,3]. The second category includes spaces in fully closed structures, such as arcade-type markets, stadia, second-skin façades, geodesic houses and glass houses, which are protected from precipitation and are not directly exposed to outdoor conditions [4,5,6,7]. As a rule, structural configuration and aesthetics have been the main concern when designing semi-outdoor spaces, while only a few studies have been performed on how they affect the energy demand of a building.

Croome simulated a case where a dome-shaped double membrane was used to enclose a group of buildings in the very cold climate of northern Canada and found that the energy use of the buildings was reduced by 16% [8]. Lin and Zmeureanu [9] evaluated the effect of transparent dome-shaped shield on the heating energy demand of a house inside the shield in the climate of Montreal, which is very cold in winter. They developed a transient three-dimensional thermal and airflow (3D-TAF) model, considering the interactions between the ambient conditions, dome, house and ground, the temperature distribution above the shield surface outside the dome, the air temperature distribution inside the dome and the pattern of air flow that developed. An annual 62.6% reduction of the heating energy needs was indicated in the dome-covered house compared to the stand alone house, under the climatic conditions of Montreal. The reduction was attributed to reduced infiltration losses, reduced convective heat losses through the walls, roof, floor and windows and increased air temperature around the house. In another study Lin et al. [10] developed a mathematical model considering the solar radiation combined with a transient thermal model through walls and glazing and an air flow model inside the dome. The effect on the heating load was evaluated in two case studies, indicating a reduction of 92.9% in Montreal, Canada and of 56.3% in Yellowknife, Canada. The reductions were attributed to the solar radiation that was trapped, the increased air temperature and the reduced wind speed inside the dome compared to the conditions outdoors.

The purpose of the present study was to investigate the effects on the energy use of a building when a climate shield that creates a semi-outdoor space is present, using two case study buildings which have different building and shield geometries, EMBRACE (Fig. 1) and Dome of Visions (DoV) (Fig. 2). The buildings are partially or entirely surrounded by a transparent shield, such that a semi-outdoor space is created, protected from precipitation and from being directly exposed to ambient conditions. The hypothesis was that the heating and cooling loads of the inner buildings would be reduced, while extra living space would be created for the occupants. This space would provide the occupants with a tempered zone in which occupants would be tolerant to a broader range of thermal conditions compared to indoors [11] in which clothing insulation could be adjusted seasonally [12].

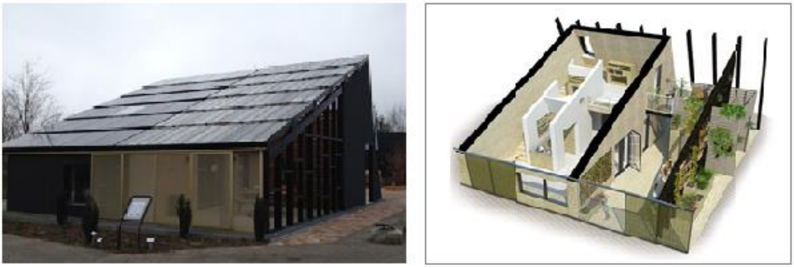

Fig. 1: Photo of EMBRACE from outside (left) and rendering with the inside view (right) [13]

Fig. 2: Photo of Dome of Visions from outside (left) [14] and inside (right) [15]

2. Methodology

2.1 Case studies

EMBRACE was designed by students of the Technical University of Denmark for the Solar Decathlon Competition Europe 2014. It is a lightweight, two-person dwelling of 63 m^2 currently located in Nordborg, Denmark. Attached to the north and east sides of the building is a transparent shield creating a semi-outdoor space. The building is only partially covered, as the roof, the south and the west sides of the building are fully exposed to ambient conditions.

Dome of Visions (DoV) is a two-person dwelling of 84m^2 enclosed in a dome-shaped polycarbonate shield, currently located in Copenhagen, Denmark. The whole inner building is protected from precipitation and from being directly exposed to ambient conditions. A Danish reference weather year was used for both simulations.

Table 1 shows the area and the average U-values of the basic construction elements of the two buildings.

Table 1. Areas and U-values of the basic construction elements [13,14]

	Area [m^2]	U-value [W/m^2K]
EMBRACE		
Windows	14.5	0.91
External walls	102.6	0.08
Floor towards ground	43.4	0.07
Roof	60.3	0.08
Dome of Visions		
Windows	48.3	2.10
External walls	106.4	0.34
Floor towards ground	65.0	0.34
Roof	65.0	0.34

2.2 Simulation procedure

The simulation software IDA Indoor Climate and Energy (ICE, version 4.6.2) was used for the investigation. In order to determine the energy demand of the buildings, load calculations were performed using ideal room units. Ideal room units are to be used to condition one zone when no detailed information about an actual room unit is available. They have no given physical location on any room surface and are not connected to the HVAC system of the building [16]. The load calculations were performed as dynamic simulations with the weather file Design Reference Year (DRY) for Copenhagen [17]. In every case examined, the peak load in W/m^2 and the energy in kWh were determined. The peak load was calculated as the total load divided by the total heated floor area, namely the area of the inner building, as the semi-outdoor area was not conditioned.

Both buildings were implemented in the building simulation program as multi-zone models. Regarding EMBRACE, the building was designed within the simulation tool, as precisely as possible, in terms of both geometry and materials. The semi-outdoor space was considered as a separate zone of the building and its walls were assumed to consist entirely of window elements with appropriate properties resembling those of the actual polycarbonate shield. A similar approach was followed for DoV, but in this case the shield shape was simplified geometrically due to software limitations.

Each building was simulated both with and without the shield, in order to identify the effect of the shield on the energy demand of the buildings. The demand was determined separately during the heating season (October-April), during the cooling season (May-September) and during the cooling season with natural ventilation in the semi-outdoor space. During the heating season ideal heaters were used, while during the cooling season ideal coolers were used together with appropriate internal gains in each zone. The natural ventilation strategies implemented in the building models resembled those of the actual operation of the building. In the semi-outdoor space of EMBRACE, two doors on the south façade and the upper windows on the north façade were scheduled to open simultaneously during the cooling season between 8-17 hours daily. In the semi-outdoor area of DoV, the existing side gaps around the deck were modelled as windows which were scheduled to be open throughout the cooling season. The top of the roof was also modelled as a window, scheduled to be open throughout the summer months and between 10-18 hours during the transition periods (April, May, and September). Finally, the infiltration assumed for each core building was 0.1 ach for EMBRACE and 0.2 ach for DoV.

3. Results

The results obtained from the load simulations for EMBRACE may be seen in Table 2 for all three simulations.

Table 2: Load calculation results for EMBRACE

	Heating		Cooling		Cooling + Natural Ventilation	
	Peak W/m^2	*Energy Demand kWh*	*Peak W/m^2*	*Energy Demand kWh*	*Peak W/m^2*	*Energy Demand kWh*
Without shield	20.1	3220	36.6	1553	35.1	1320
With shield	19.7	3122	32.3	1548	24.3	1128
% Difference	-2.2%	-3.1%	25.7%	-0.3%	-30.8%	-14.6%

Comparing the heating needs of the unshielded and the shielded version of EMBRACE only a minor reduction was found in both energy demand (-3.1%) and peak load (-2.2%). The peak cooling load was significantly increased (25.7%), while the energy demand during the cooling season was not affected by the addition of the shield. However, when natural ventilation was implemented in the semi-outdoor space of the shielded version, the peak cooling load decreased by 31%, while the energy demand throughout the cooling period decreased by 15%. The difference could be attributed to the fact that, due to the presence of the climate shield, the solar radiation accumulated in the inner building was reduced, while simultaneously the warm air in the semi-outdoor space was allowed to escape by natural ventilation.

The results obtained from the load simulations for the Dome of Visions may be seen in Table 3 for all three simulations.

Table 3: Load calculation results for Dome of Visions

	Heating		Cooling		Cooling + Natural Ventilation	
	Peak W/m^2	*Energy Demand kWh*	*Peak W/m^2*	*Energy Demand kWh*	*Peak W/m^2*	*Energy Demand kWh*
Without shield	72.4	10304	114.3	5052	114.3	5052
With shield	60.9	6457	156.5	10598	74.5	1938
% Difference	-15.9%	-37.7%	36.9%	109.8%	-34.8%	-61.6%

The addition of the climate shield around the building of the DoV reduced the heating demand by 16% in terms of peak load and by 38% of total energy demand during the heating season. However, the cooling demand doubled during the cooling season and the peak cooling load was 37% higher. When natural ventilation was implemented in the semi-outdoor space of the DoV, the peak cooling load was reduced by 35%, while the energy demand was reduced by 62%. As for EMBRACE, the solar gains in the inner building were reduced due to the addition of the shield, and the natural ventilation prevented solar-heated air from being trapped in the semi-outdoor space.

4. Discussion

The results show that the two climate shields affected the energy performance of each building differently. The two buildings that were simulated differ considerably in geometry and materials. EMBRACE is very well insulated, as it was designed to be a passive house, whereas DoV is a building with a very low level of insulation. This would explain why the heating and cooling loads calculated for the DoV were much higher than for EMBRACE. The difference in the geometry of each shield and the way it is connected to each building critically affected the outcome of the simulations. These differences would mean that the buildings are not directly comparable, but the results still followed the same trends, which is a strong indicator of the impact of a climate shield on any building.

Both buildings appear to be positively affected by the addition of the shield in terms of energy use and peak loads during heating season, whereas during cooling season the effect was negative. This was expected, since the inner buildings were fully or partially enclosed in the shield, so solar heat was accumulated in the semi-outdoor space, i.e. a greenhouse effect was created. Natural ventilation in the semi-outdoor space eliminated this effect and the energy use for cooling of both buildings was considerably reduced compared to the unshielded versions of the buildings. It should be pointed out that the natural ventilation strategy that was simulated in each building was the one actually used in that building, not the optimal one. Optimization would further improve the results, but a computational fluid dynamic (CFD) analysis should then be applied to evaluate each strategy and ensure that it does not result in a problematic environment for the occupants.

The investigation was performed under the climatic conditions of Copenhagen, extending the previous work cited in Canada. Since buildings with a semi-outdoor space are not widely used, there is limited experience of the economic aspects of such projects, so a technical and economic analysis of the feasibility of such an investment is crucial. Finally, the practicability of implementing such structures should also be examined, as there could be many limitations that were not studied in this study, such as the cost and durability of the different climate shields.

5. Conclusion

- The shape of the shield and the way that it was connected to the building critically affected the magnitude of the impact of the shield on the building.

- The results for both buildings revealed the same trend. The peak heating load and energy use during the heating season were reduced by the shield was added, while the energy use for cooling increased.

- In both buildings, implementing natural ventilation in the semi-outdoor space considerably reduced the peak cooling load and the energy demand in the cooling season.

- The addition of a shield was beneficial for both buildings in terms of peak loads and energy use provided that a natural ventilation strategy was implemented in the semi-outdoor space, even though actual rather than optimal natural ventilation was simulated.

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