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Aramid/glass fiber-reinforced thermal break – thermal and structural performance

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ABSTRACT

Energetically weak points in thermally insulated building envelopes are formed by thermal breaks that are implemented to structurally connect external balconies to internal slabs. Current thermal breaks comprise stainless steel bars that penetrate the insulation layer and thus cause significant thermal losses. A new thermal break composed of highly insulating aramid and glass fiber-reinforced polymer (AFRP and GFRP) components and aerogel granulate insulation materials was developed and the first prototypes of the load-bearing components were experimentally investigated. The use of AFRP leads to an excellent thermal performance with linear thermal transmittance values of below 0.15 W/m K. The experimental prototype investigations confirmed the targeted ductile failure mode through concrete crushing in the component–concrete interfaces. The serviceability limit state conditions are met for a targeted balcony cantilever span of 4.0 m. The material-tailored components can be manufactured by fully automated processes such as filament and tape winding and pultrusion to economically produce large quantities within a short time.

1. Introduction

Against a background of increasingly strict sustainability requirements in our society, the reduction of the energy consumption of building stock represents a major challenge. As building stock accounts for almost 40% of total energy consumption in the European Union, the aim is to design all new buildings as nearly zero-energy buildings (NZEB) by the end of 2020 [1]. One major cause of energy losses in buildings is thermal bridges in the building envelope, created by any interruption of the insulation layer or locations with reduced thermal resistance [2]. Up to 30% of total heat losses of buildings can occur through thermal bridges in particular cases [3].

A typical and frequent thermal bridge in building envelopes is caused by the penetration of the envelope by an internal concrete slab in order to create an external cantilevered balcony, as shown in Fig. 1 [4,5]. The insulation layer is interrupted and a thermal break element is usually installed between the inner slab and the balcony to provide additional thermal resistance. However, the thermal insulation capability of such elements is much reduced compared to that of the surrounding wall, since they comprise stainless steel bars to provide structural continuity, i.e. transfer of exterior balcony bending moments and shear forces to the interior slab. Stainless steel bars, however, exhibit much higher thermal conductivity than commonly used insulating materials, such as mineral wool or polyurethane (PU), see Table 1. Although the penetrating total bar cross section is normally small (depending on the balcony span), thermal losses may still be considerable.

The thermal performance of such thermal breaks can be evaluated by the linear thermal transmittance, ψ, defined according to ISO 10211:2007 [6]. The value represents the heat losses through the elements in addition to the losses through the surrounding wall. In Switzerland, Swiss Code SIA 380/1 [7] specifies a corresponding limit value of $\psi \leqslant 0.30$ W/m K and target value of $\psi \leqslant 0.15$ W/m K, the former being obligatory for all products on the market. In order to approach the target value with traditional thermal breaks (stainless steel bars), the possible balcony span is, in most cases, significantly reduced.

In recent years, attempts have been made to replace stainless steel bars with glass fiber-reinforced polymer (GFRP) composite components, whose thermal conductivity is much lower, see Table 1, to thermally improve this construction detail [4,8,9]. However, the comparatively low stiffness of GFRP materials results in a stiffness-driven thermal break design, in order to meet the deflection limits of the balcony. The required amount of GFRP material is thus increased, leading to an increase in cost. Furthermore, no appropriate anchoring of the upper GFRP tensile component has been developed; the required anchoring length of straight

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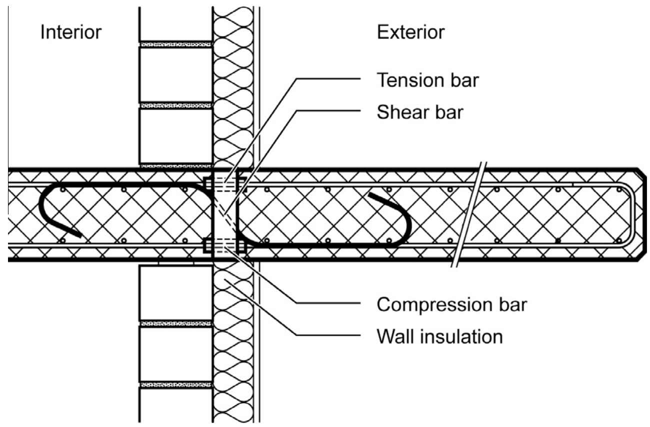

Fig. 1. Traditional stainless steel thermal break for balconies [4].

Table 1
Thermal conductivity of thermal break materials (aerogel data from [11], remaining data from [12]).

Material	Thermal conductivity (W/m K)
Stainless steel bars	15.0
Reinforced concrete	2.5
Glass fibers	1.0
Aramid fibers	0.04
Epoxy resin	0.52
GFRP laminate	0.80
Aramid laminate	0.13
Mineral wool	0.035
PU foam	0.028
Aerogel granulate	0.013

pultruded GFRP bars, for instance, is much longer than that of steel bars, hindering the easy handling and transportation of the prefabricated thermal breaks. Bars with hooked ends cannot be used because the elements cannot be threaded from the top into the pre-installed slab steel reinforcement (see structural concept description below).

In this work, a new approach has been pursued and a new FRP thermal break was conceived with superior thermal and structural performance compared to existing steel and GFRP elements. The aim was to develop a thermal break that can meet the target value of Swiss code [7] ($\psi \leqslant 0.15$ W/m K) and nevertheless enables significant cantilever spans of up to 4.0 m. The main novelty is the use of aramid fibers, which exhibit much lower thermal conductivity and higher stiffness than glass fibers, see Table 1. Furthermore, the development of more FRP material-tailored (and thus economical) structural components was the aim rather than purely substituting steel by GFRP bars. This paper describes the concept of the new thermal break and evaluates its thermal and structural performance through experimental and numerical investigations. The long-term effects such as creep and exposure to alkaline environments of the parts embedded in the concrete are also addressed.

2. Thermal and structural concept

2.1. Overview

The material selection for the new thermal break element was primarily driven by thermal performance criteria, i.e. the materials' thermal conductivity. In this respect, aramid fibers and aramid fiber-reinforced polymer (AFRP) composite laminates exhibit much better performance than glass fibers and GFRP laminates, see Table 1. However, aramid fibers have low compressive strength and their use for components subjected to high compressive stresses is limited [10], which is why glass fibers and GFRP laminates could not be completely excluded in the new design (see structural concept description below). However, GFRP materials still offer enhanced thermal behavior compared to stainless steel. An improvement of existing thermal breaks was also aimed at for the non-load-bearing insulation material of the element (between the adjacent concrete slabs) by selecting aerogel granulate [11], which offers a much better thermal performance than mineral wool or PU foam, see Table 1.

The structural concept of the new thermal break is based on a simple 45°-N-shape truss system in which the load-bearing components of the element are incorporated and transfer the bending moments and shear forces from the balcony cantilever to the inner slab, as shown in Fig. 2. The negative bending moment is transferred by an upper tensile and lower compressive force (equal in magnitude), while the shear force is transferred by a diagonal compression strut. Based on this concept, an AFRP loop component was conceived to bear the upper tensile force. Furthermore, a combined A/GFRP hexagon component, consisting of an upper AFRP or GFRP sandwich and a lower short and compact GFRP bar, was developed to transfer the two compressive forces from shear and bending, as described in detail below and shown in Figs. 2 and 3a. Loop and hexagon components are assembled together in a prefabricated, 50 mm-wide PVC box, which is subsequently filled with the aerogel granulate. The box is composed of three parts and the height of the middle part (which does not contain any component penetrations) can be adapted to the slab thickness. On the construction site, the prefabricated thermal break (aerogel-filled box with loops and hexagons) can then easily be inserted from the top into a prepared recess in the already installed concrete steel reinforcement, as shown in Fig. 3b. The spacing of the loops and hexagons, along the balcony length depends on the load level, i.e. the cantilever span of the balcony. The basic thermal break unit is 150 mm wide, comprising one loop and two hexagon components; Fig. 3 shows the densest arrangement with the highest load-bearing capacity. The short GFRP bar of the hexagon can be arranged flush with the bottom side of the slab when no fire safety is required, i.e. in cases where the balcony does not represent an emergency exit (which is normally the case). Otherwise, the component can be raised by 10 mm to provide space for a fire protection layer, as shown in Fig. 2.

In the pre-design phase, the dimensions of the A/GFRP components, i.e. the cross-sectional areas in particular, used in the following were derived from theory and manufacturer datasheets. Since AFRP and GFRP composites are brittle materials, the AFRP loop

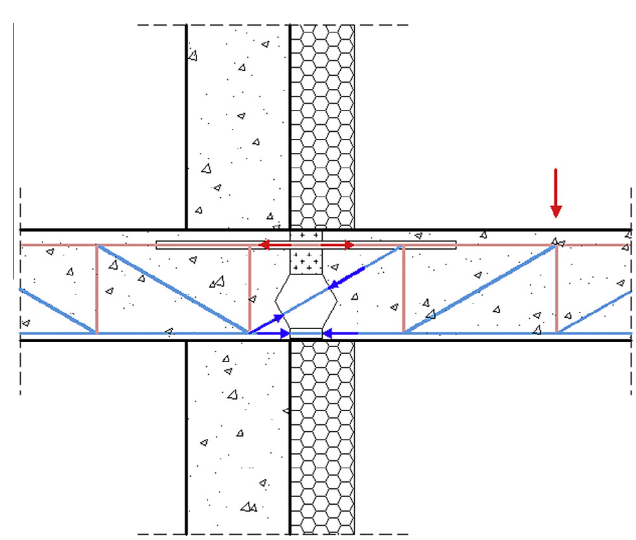

Fig. 2. Structural concept of new A/GFRP thermal break.