Composite behaviour of wide sandwich panels with thin high performance concrete wythes with and without Thermomass shear connectors

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ABSTRACT: To partly address the future sustainability of energy use in buildings, there is a programme in Europe to retrofit domestic and commercial buildings with non-load bearing insulated re-cladding and over-cladding pre-cast concrete sandwich panels. Recent research work has shown that limited composite action is possible between the inner and outer wythes depending on the type of non-conductive shear connector used and the stiffness of the insulation. This paper reports on the development of a sustainable mix design incorporating recycled aggregates to produce high strength 20mm thick fibre-reinforced concrete wythes. These were incorporated into the manufacture of wide sandwich panels with five silicone-bonded layers of XPS insulation, making up a panel which was 220mm thick. These model panels were then tested in flexure using displacement control tests to establish the effectiveness of the composite action and the extent of post-cracking toughness of the panels in resisting flexural loads. During the observation of good composite action in the elastic range for the shear-connected panel, it was noted that the lower wythe cracked first due to its stiff support on the end bearings while the upper wythe flexed less due to effectively sitting on the insulation acting as an elastic foundation. This panel exhibited considerable post-cracking toughness, with observable interleaf shear movement in the insulation. On the other hand, in the absence of shear connectors, the top and bottom wythes both cracked under low load while a small residual strength was offered by the fibres pulling out and the shear sliding of the insulation, albeit with considerable flexibility.

KEY WORDS: Sandwich cladding panels; Shear connectors; High performance concrete

1 INTRODUCTION

Precast concrete sandwich panels can be used as over-cladding or re-cladding of building facades in the drive to secure a more sustainable carbon cost of building energy provision. A considerable body of research has been undertaken in the last decade into the structural behaviour of thick and thin sandwich panels with different types of shear connectors [1-3]. The desire to increase the panel width to accommodate higher levels of insulation is tempered by the need to use shear connectors to ensure composite action between the two leaves (or wythes) of the panel, while preventing thermal bridging [2]. Due to their additional weight on existing buildings when used in retrofit applications, there is also a drive to use thinner high strength concrete wythes [3]. Research has been done on the effect of using non-conductive connectors (compared to none) to show the advantages of developing the greatest composite action possible, despite the thinness of the wythes [4, 5]. Generally, XPS insulation is affordable and, when thick enough, offers reasonable thermal properties [6], which when combined with ultra-high performance concrete (UHPC) wythes, yield an efficient panel both thermally and structurally [7]. The ultra-high strength of a more sustainable concrete mix is achieved through several newer technologies, including the use of very low water cement ratios, with a superplasticiser, ground granulated blast furnace (GGBS) and Silica Fume (SF) as Portland cement substitutes, supplemented by the inclusion of hybrid fibres and recycled concrete aggregates. The fibres minimise plastic and long term drying shrinkage cracking [5, 8, 9] while the use of GGBS [10] and SF [11, 12] reduce the carbon footprint and improve the long term strength if properly cured. It is also more sustainable to utilise recycled concrete as the aggregate in the mix [13, 14], though this is usually associated with strength loss due to the porosity and weakness of adhered cement paste. This can be overcome by pre-soaking the aggregate in a SF/water slurry to block up the pores in the adhered paste [15].

The aim of this work, which was part of an MSc research project of one of the co-authors, was to investigate the composite behaviour of a sandwich panel in which the amount of insulation was increased by increasing the overall thickness of the panel together with decreasing the thickness of the wythes. The wythes were formed using a sustainable concrete mix that achieved high strength despite the use of recycled aggregates. The presence or absence of shear connectors will, when tested in flexure, establish whether or not composite action is actually being achieved despite the wide separation of the wythes. From previous work [2, 3, 5], the use of fibre reinforced plastic (FRP - ™Thermomass) shear connectors (Figure 1) will deliver the optimum chance of making these thin wythe - wide panels work structurally.

2 METHODOLOGY

The new concrete mix for the wythes in the concrete panels had first to be adapted from previously successful ultra-high performance mixes with normal aggregates [2 – 4] (with compressive strengths of over 125MPa), where principally the novelty here is in the replacement of quarried limestone

Figure 1. 200mm long FRP shear connector

aggregate with a recycled concrete aggregate. Furthermore, the inclusion of a 180 mm width of insulation sheets imposed a greater challenge in obtaining good composite action between the two wythes in flexure. In order to understand the extent of the composite action achieved, the insulation and a single wythe with and without ribs were tested first, then two composite panels were tested, one with and one without FRP shear connectors.

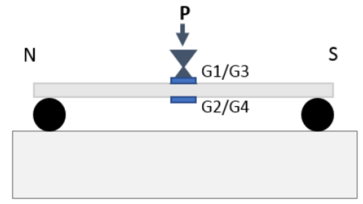
The optimum mix constituents, found after five iterations of trial mixes [16], are listed in Table 1, where the quantity of SF used was based on what was strictly required just to coat the recycled aggregates, as determined from a recycled aggregate water-absorption test. The water binder ratio was 0.30 and a Betocarb filler was included to improve the particle packing and, hence, strength. A dosage of 39 kg/m^3 of 30 mm hooked steel fibres were also added to the mix and, while normally some polyproplyene fibres would also be added to prevent plastic shrinkage cracking, on this occasion none was required due to the test specimen size.

The sandwich panels had overall dimensions of 900 mm span by 600 mm width by 220 mm deep, where the wythes were each 20 mm thick with a 35x35 mm deep rib in the span direction only in the case of the shear connected panel to accommodate better anchorage of the 200 mm FRP connectors. The XPS insulation came in five sheets, bonded together with silicone in the laboratory, making up a 180 mm thick slab of insulation. For the unconnected panel, the wythes were poured individually on the same day and the panel was assembled subsequently, with no physical connection between the wythes or insulation. The shear connected panel had to have the connectors embedded in both wythes and so were poured on two consecutive days, one on top of the other, separated by the insulation with the concrete and connectors cast insitu.

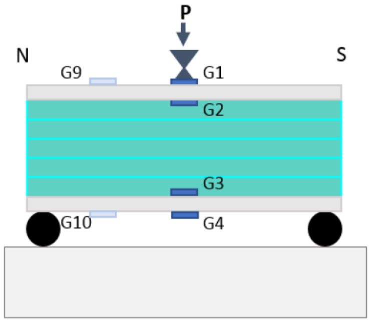
The flexural test arrangement for the plain and sandwich slabs are shown in Figure 2 (a) and (b) respectively. The arrangement was composed of a simply supported slab at either end of the 900 mm span with a central line load across the full 600 mm width, applied through an actuator with displacement control application at a rate of 1 mm per minute. The significance of the fact that displacement control was used was that the actuator imposed this displacement to the load spreader and measured, with an internal load cell, the subsequent load resistance offered by the beam under that displacement increment. In this way, a load was not imposed on the beam, but its load resistance was recorded as displacement imposition proceeded.

Table 1. Mix constituents for thin concrete wythes

Constituent	Mass (kg) per m^3	Mass (kg) per Wythe
10mm Recycled Aggregate	760	17.5
Sand	715	16.5
Betocarb Filler	400	9.2
Silica Fume	109	2.5
CEM I	254	5.9
GGBS	254	5.9
Water	154	3.6
Glenium 51 Superplasticiser	18	0.4
Steel Fibres (30mm)	39	0.9
TOTAL	2703	62.4



(a)



(b)

Figure 2(a) Flexural test arrangement for a single wythe and (b) typical sandwich panel with clear span 850mm

The readings from up to 10 strain gauges (depending on the case) and 4 linear variable displacement transformer (LVDT) transducers were logged twice a second to identify the key deformation changes and the top to bottom strain distributions at the concrete/insulation interfaces at mid span. The sensitivity of strain gauges is usually defined by a gauge factor, which in this case is 2.08%. The gauges used were 120 Ohm with a 60mm gauge length.

It is recognised that a limitation of this work is that only one of each panel type was tested, due to the complexity of each of several test types and the research restrictions on MSc projects in the laboratory. Hence, no comments on variability can be made here, but would be essential to explore in future projects.

Concrete compressive cube and beam flexural strengths of specimens were tested at 7, 28 and 56 days, as well as Young's modulus, through cylinder testing, at 28 days for all wythe pours.

3 RESULTS AND DISCUSSION

3.1 High strength concrete properties

The 28 day average compressive strengths (of two cubes) of natural aggregate, recycled aggregate (RA) and recycled aggregate with SF concretes were 97 MPa, 80 MPa and 90 MPa respectively while the equivalent flexural strengths were 15.3 MPa, 11.0 MPa and 13.5 MPa. The presence of the RA reduced the strength somewhat as expected due to the adhered mortar while the addition of the SF ameliorated this effect, but not wholly, again as expected. The elastic modulus of the wythe concrete at 28 days was 44.5 GPa, a high value for 90MPa concrete. It may be deemed that the concrete for the wythes was a high performance concrete.

3.2 Insulation and individual wythe testing

3.2.1 Insulation testing

A typical plot of load resistance provided by the insulation when tested in flexure over time is given in Figure 3. As the test machine had a 400 kN test capacity and it was being used at the very low end of its range, a considerable amount of noise is evident in this plot. With a peak resistive load of 0.50 kN under a maximum imposed deflection of 24 mm, the loading was halted upon reaching the maximum travel of the actuator in that configuration. The response was still linear at this large displacement and the insulation was observed to be very flexible (with a modulus, E of approximately 0.75MPa) with almost 100% deflection recovery on unloading. Its contribution to the load carrying capacity of sandwich panels will be observed to be not insignificant post-cracking in the panel tests which follow.

Note that in Figure 3, and some subsequent plots (such as Figures 5 and 7), there is a short initial period from time equals zero when zero load exists. This is because the actuator head is not actually touching the load spreader when the data logging occurs and so resistive load is only experienced (and thus recorded) when the actuator actually engages with the beam through the load spreader after some initial displacement of the actuator head. Furthermore, the x-axis in Figure 3 represents the recorded time as the displacement proceeds. This can be converted into a displacement knowing the displacement rate (1mm/min), but for the purposes of demonstrating a linear load response with applied displacement, Figure 3 suffices, as do other plots with a time axis in this paper.

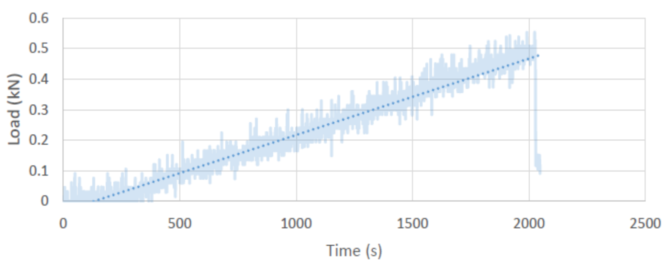


Figure 3. Load capacity of XPS insulation under a flexural load up to a maximum deflection of 33.3 mm at 2000 seconds

3.2.2 Individual wythe testing without ribs

To understand panel composite behaviour it is necessary to understand the flexural response of a single wythe, both ribbed and unribbed. Considering the unribbed wythe first, from Figure 4 it may be observed that the peak load was 2.6 kN and the wythe sustained a residual load of at least 1.5kN up to a maximum deflection 33.5 mm. The peak load corresponds to about 14.0 MPa elastic tensile stress on the bottom face. In the plot, A is when the first crack occurs, while B-C represents crack propagation on the underside of the wythe, demonstrating the residual load capacity offered by the pull-out resistance of the fibres. Evidence of sudden fibre pull-out can be seen at point C. The rise at the end of the test is when the wythe touches the bottom of test rig due to large deflections and is irrelevant. It is evident that, in displacement control mode, there is considerable post-cracking toughness of the wythes, as offered by the fibres and the typical brittle failure of high strength concrete has thus been avoided.

It should be noted that if a load control test had been used instead (where an increasing load is imposed on the beam by the actuator head moving a distance as necessary to apply the next increment in resistive load by the beam), the linear part of the curve in Figure 4 would be very similar. However, at the peak load the head would accelerate in the vain attempt of applying the next load increment, which the beam does not have the capacity to provide post-cracking. In this case, failure would be sudden and brittle. This is a common feature for most types of fibre reinforced concrete, but is not examined here.

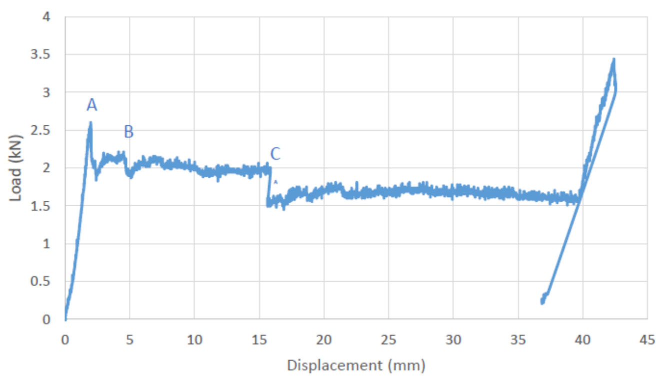


Figure 4. Load –mid span displacement plot for single unribbed wythe in flexure

Figure 5 presents the equivalent G2 (see Figure 2(a)) tensile strain against time plot, where strain points A to C correspond to the load deflection plot. The strain is virtually constant post peak because the gauge is not where the crack appears and so, as the crack visibly opens, restrained by the fibres, the wythe holds its load capacity (as seen in Figure 4) and so the strain does not change appreciably at that point in the wythe.

The corresponding stress-strain plot in Figure 6 demonstrates almost ideal linearly elastic and perfectly plastic behaviour. However, some of the detail of the plots in Figures 4 and 5 would be lost if only Figure 6 were shown, showing the benefit of their inclusion.

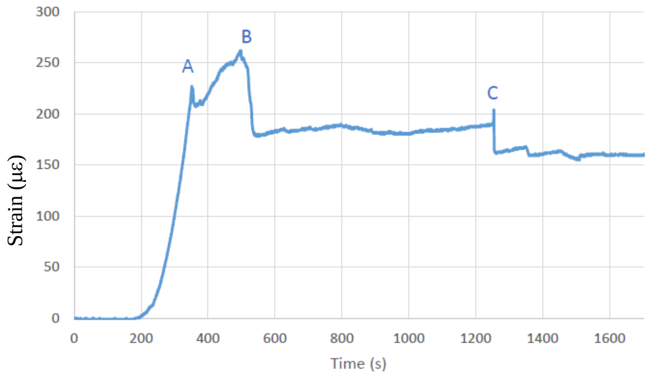


Figure 5. Strain (gauge G2 in Figure 2(a)) over time for a single unribbed wythe in flexure

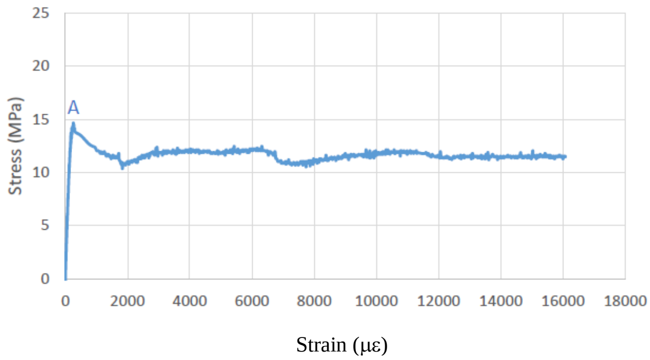


Figure 6. Stress versus microstrain (G2) for single unribbed wythe in flexure

3.2.3 *Individual wythe testing with ribs*

Similar to the previous plots, an examination of load resistance capacity of a ribbed wythe over time (Figure 7) reveals points A-D, which represent the initial crack formation, propagation and opening up (Figure 8). However, with the addition of the 35 mm deep rib, the peak load is 3.7 kN corresponding to peak elastic stress of 30 MPa, approximately 30% higher than the wythe without the rib. In this case, all main cracks occurred in the rib within 7 minutes (that is, 7mm imposed displacement) of a 45 minute test, whereupon the fibres maintained the load resistance up to 30 mm deflection, some 20 times the serviceability deflection.

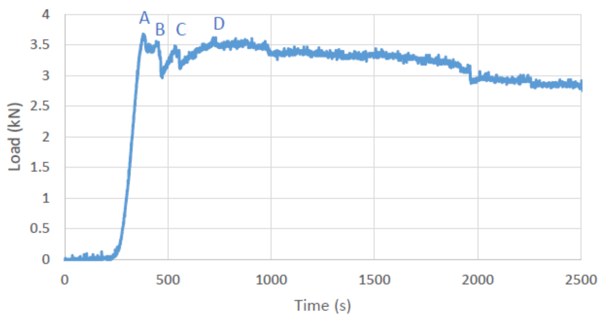


Figure 7. Load resistance capacity over time for single ribbed wythe in flexure

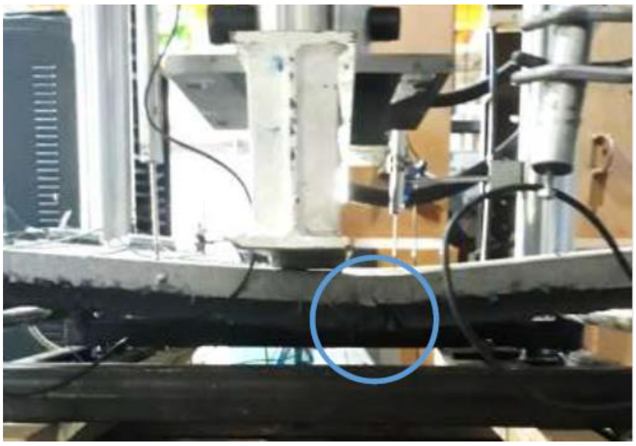


Figure 8. Fully developed crack under peak load for ribbed single wythe

3.3 *Composite panel testing*

3.3.1 *Without shear connectors*

In the case of the unconnected panel, the wythes were not connected together nor to the insulation in any way but the insulation sheets were “glued” together with silicone, primarily for handling purposes. Under a flexural load, the bottom face of the lower wythe was the first to crack because it took much of initial load as indicated by different readings in the strain gauges in the two wythes. This was due to the lower wythe having a rigid (against vertical movement) simple support at the edge although experiencing a more uniform load (as transmitted through the insulation depth). The top wythe was effectively experiencing a concentrated line load in the middle of the span, but sitting on a less rigid elastic foundation (the highly flexible insulation) and so experienced less flexural stress initially. Thus the wythes initially jointly take a load up to approximately 2.5 kN, whereupon the bottom one cracks and the top wythe now takes the main proportion of the load. The insulation also takes a small amount, about 0.5kN according to the insulation tests (Figure 3). From previous research [2], thicker inner wythes (120mm thick) ensure that the outer leaf cracks first and thus cracks are seen readily on the outside of such structures. The thinner, hidden, inner wythe here changes that because it cracks first and damage can remain undetected in the inner leaf after loading. Despite this, there is a significant sustainability gain from having two high performance thin wythes because panels are lighter and have a lower carbon footprint.

In Figure 9, the top ribbed wythe takes about 3.5kN before it cracks (at point D), similar to the single wythe response. This indicates, not surprisingly, that there exists practically no composite action, just a sequenced failure of individual wythes. The insulation slides horizontally due to shear (as may be observed from the staggered black marker vertical lines in Figure 10) but does not fail (nor did it in Figure 3 under a similar deflection) and so the fibres and insulation continue to contribute to load resistance capacity. It may also be observed that the lower wythe now makes no contribution and the top wythe, though cracked, continues to offer some load resistance to point E in Figure 9, where the crack in the upper wythe is fully developed and the fibres hold the panel together, with a

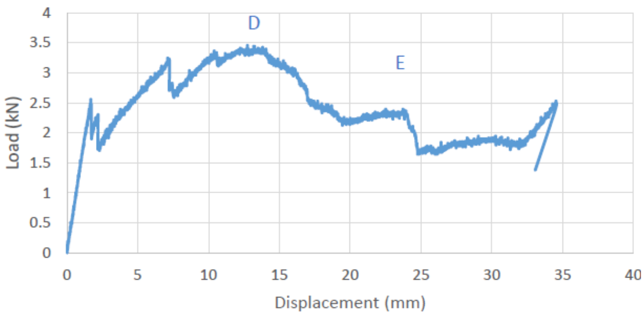


Figure 9. Load –mid span displacement plot for the unconnected sandwich panel

Figure 10. Image of the unconnected sandwich panel close to failure

sudden drop in load carrying capacity (at E) with continued forced displacement by the actuator.

3.3.2 With shear connectors

After the elastic stage of loading to almost 6kN (see Figure 11), micro cracks propagate across the bottom face of the bottom wythe. At this stage good evidence of composite action exists because both of the strain gauges in the bottom wythe (gauges G3 and G4 in Figure 2(b)) are in tension up to the peak load of 11.2kN, some three times the individual ribbed wythe's capacity and 30% larger than the sum of the three individual component's capacities. Referring to Figure 2 (b), gauges G1 to G3 at 13 mm into the test are approximately -500 με (compression), +8000 με and +16,000 με (both in tension) respectively, where the latter two strain gauges had just broken, while bottom gauge G4 had broken, also at +16,000 με at 10 mm into the test at location C in Figure 11. The bottom wythe was now fully cracked and a sudden drop in load occurred due to a large crack through the full depth of the bottom wythe. However, it continued to have a contribution as the shear connectors keep the top and bottom parts connected and the fibres bridged the cracks in both wythes. With further imposed deflection, the insulation tore in tension, initially on the bottom and latterly closer to the top (see Figure 12). The insulation sheets also delaminated and moved laterally (see Figure 12) as the top wythe cracked and the fibres further slipped in pull-out (as observed by the step changes in Figure 11). Before the load was removed, the fibres in the top wythe, together with the residual capacity of the insulation and fibres in the lower wythe, through the shear connectors, still had load resistance of over 4kN, representing more than an individual wythe's resistance.

The load-displacement response in Figure 11 represents a high degree of post-cracking toughness, quite different in behaviour and capacity compared to the unconnected panel, with peak load capacity 3.2 times higher. Clearly, the connected panel has a considerable degree of composite behaviour despite the large width of separation between the two layers and the reduced concrete strength due to the presence of recycled aggregate. In this sense, though not optimised, this investigation into a more sustainable wide sandwich panel with very thin wythes has been shown to be successful in evidencing the potential for this technology in future research.

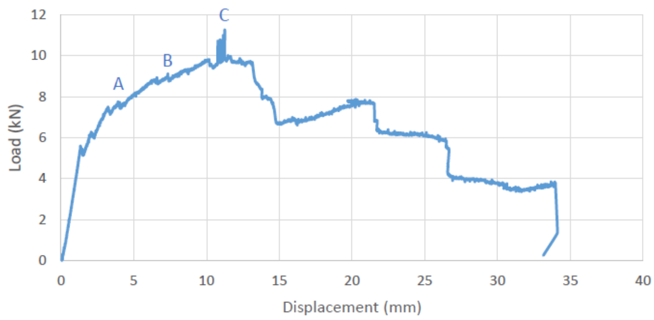


Figure 11. Load – mid span displacement plot for the shear connected sandwich panel

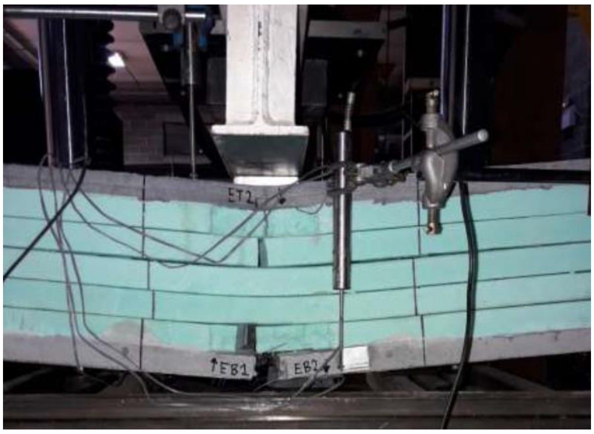


Figure 12. Image of the shear connected sandwich panel close to failure

4 CONCLUSIONS

This paper has provided evidence of how to manufacture a high strength GGBS concrete mix with high strength and flexibility despite the presence of recycled concrete aggregate, pre-treated with silica fume and utilising fibres to avoid sudden brittle failure when tested using displacement control. The 28 day compressive and flexural strengths were approximately 90 MPa and 13 MPa respectively, with an elastic modulus of about

45MPa. The fibres contributed about 10% and 16% to the compressive and flexural strengths respectively and the SF treatment of the recycled aggregate about a further 10% to both.

When this concrete was used to manufacture very thin (20mm) wythe sandwich panels with shear connectors, significant composite action was achieved between the two wythes despite the large width (180mm) of the insulating layer. The panel's elastic moment capacity was about 2.25 kN.m (which equates to a wind load of over 3kN/m^2 on a 3m span), 3.5 times the flexural load capacity of an individual wythe. The peak load of about 11.3 kN was maintained under an imposed displacement of 33.3 mm. Considerable post-cracking toughness was thus attained, where the peak load was well maintained over many times the deflection serviceability limit, through a combination of actions of the insulation's flexibility (without tearing), the effectiveness of the Thermomass shear connectors in keeping the two wythes connected and the fibres in both wythes providing pull-out residual load capacity even under high deformations ina cracked state. It was noted that the inner wythe failed first which may not be desirable in retrofit applications because the associated cracking would not be visible from the external surface. Therefore, a modest increase in the inner wythe thickness may be necessary to avoid this hidden damage when overloaded by wind or impact.

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