Construction and Building Materials 300 (2021) 123974

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental testing of a composite structural system using tile vaults as integrated formwork for reinforced concrete

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HIGHLIGHTS

- Proposal of efficient construction method for RC shells using tile-vaulted formwork.
- Material characterization of bricks, mortar, cement, concrete and reinforcement.
- Load tests and monitoring on full-scale, composite barrel vaults.
- Successful structural behaviour of novel construction technique and prototypes.
- The method ELARM is suitable for the structural analysis of the proposed system.

ARTICLE INFO

Article history:
Received 28 December 2020
Received in revised form 18 May 2021
Accepted 12 June 2021
Available online 29 June 2021

Keywords:
Tile vault
Reinforced masonry
Formwork
Concrete shells
Experimental
ELARM

ABSTRACT

Tile vaults are unreinforced masonry structures made of thin bricks (tiles) and fast-setting mortar that can be constructed without the need of a formwork, except at the boundaries, making them inherently economic. Their slenderness and finishing make them also efficient and expressive. These qualities of tile vaulting can be enhanced by combining it with reinforced concrete creating a new composite system. The tile vault can be integrated in the final solution, as a permanent formwork, reducing construction costs and waste. A top layer of reinforced concrete rises up the strength of the composite system, whereas reinforcement reduces the thickness and opens the possibility to build structures with a formal language well beyond what is typically associated with masonry architecture. Therefore, several advantages make the system competitive compared to traditional reinforced concrete shells. This paper presents experimental research on the materials of this composite system and load tests on composite barrel vaults. The construction of full-scale prototypes has allowed a critical review of the construction process and has demonstrated the feasibility of the technique and its successful structural performance. Moreover, the analysis of this composite structures is carried out using Extended Limit Analysis of Reinforced Masonry (ELARM), provided that the reinforcement guarantees sufficient ductility. Furthermore, the data collected from the experimental research becomes a benchmark for the calibration of eventual further structural models.

1. Introduction

Concrete shell construction had its peak of popularity from the 1920s to the early 1960s, in the work of architects and engineers such as Freyssinet, Nervi, Isler, Candela and Torroja, who were fascinated by the structural efficiency and elegance of shells. Since then, the use of these constructions declined, and architects and engineers have lost their interest in a typology that has produced a vast number of exceptional architectural structures [2].

Thin concrete shell construction has not been in vogue anymore due to different reasons, among others, the complexity of their structural analysis and its construction costs, specifically the cost of the formwork, which is typically expensive, geometrically complex and materially wasteful. Contemporary examples are typically only affordable for signature buildings, for which budget constraints are not necessarily of great concern. New, expressive free-form thin concrete shells are attractive to many current designers, architects and engineers, but they are generally not

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https://doi.org/10.1016/j.conbuildmat.2021.123974
0950-0618/

affordable for most clients. On the other hand, air-inflated or modular formworks offer an inexpensive way of building concrete shells, but they suffer from strong formal restrictions, and are therefore not as appealing to designers [2,3].

One could argue that ruled surfaces might offer a solution; they can still be expressive and easier to build, since only straight pieces are needed to build the formwork. In fact, this is the way in which some master builders like Félix Candela built their remarkable architectural pieces, who claimed that it was an efficient and cheap way to construct them [4]. However, these are only partial solutions to the problems, since the geometry is still highly restricted and the formwork needs material-abundant falsework, shuttering, and foundations.

A possible approach to the construction of free shape shells may be provided by the use of tile vaults as integrated formwork. Using tile vaults as permanent formwork for concrete shells can reduce construction costs and waste, making them more economic and sustainable. The costs are reduced mainly because of the materials' inexpensiveness and the fact that no formwork and related foundations are needed [1,5,6].

Tile (also known as thin-tile, timbrel, Catalan or Guastavino) vaults are unreinforced masonry structures made with bricks and binder. The bricks are placed flat, building up two, three or more layers. Traditionally, thin bricks or tiles are used because of their lightness, which is a necessary condition to build the first layer by temporarily cantilevering out into space using gypsum or fast-setting cement. The aim of using these binders for the first layer is the quick adhesion achieved so that the bricks stick within seconds to the edge walls, arches, or stable sections already finished, avoiding the necessity of centering (Fig. 1). Using this first layer as stay-in-place formwork, the second and subsequent layers, which build up the necessary structural depth, can be set with lime or Portland cement mortar. Tile vaults are very efficient, since they have a large load-bearing capacity with high slenderness ratios [7].

This traditional construction technique has been "rediscovered" in the last few years. The development of new interactive equilibrium methods for the design and analysis of masonry structures have rekindled interest in the versatile tile vaults, resulting in a proliferation of projects worldwide featuring this technique and showing novelty in their shapes and innovation in the fields of construction and materials [9–14].

Tile vaulting combined in different manners with concrete and/or reinforcement has been used in the past with successful results by some of the architects with vast experience in tile vaulting, such as the Guastavinos, Antoni Gaudí or Luis Moya, and by other architects or engineers who were able to envisage the virtues and advantages of the traditional technique, such as Le Corbusier or Eduardo Torroja [5].

The experimental research described in this paper learns from these experiences to present an effective, economic and expressive construction technique. In specific, the paper presents the experimental investigation of four full-scale prototypes, built and load-tested in laboratory. The construction technique of a tile vault used as stay-in-place formwork for plain concrete was first assessed through the construction and testing of two tile-concrete composite barrel vaults. The second set of experiments consisted of the construction and testing of two steel-reinforced composite barrel vaults. The research has also involved the characterization of the materials composing the vaults (bricks, mortar, concrete and reinforcement) providing detailed experimental information as a basis for further development of the construction technique and/or the calibration of structural models. Furthermore, the Extended Limit Analysis of Reinforced Masonry (ELARM), first presented in [1], is proposed in section 6 of the present paper as an analysis method for the assessment of the described structural system, provided that it has a ductile response.

2. Construction system

This system consists of a tile vault with one, two or more layers of bricks, and a top layer of reinforced concrete (Fig. 2). Research on construction techniques that, although different mainly because of the construction process, present some similarities in terms of structural behaviour and materials is described in [15–17].

Fig. 1. Construction of a tile vault [8].

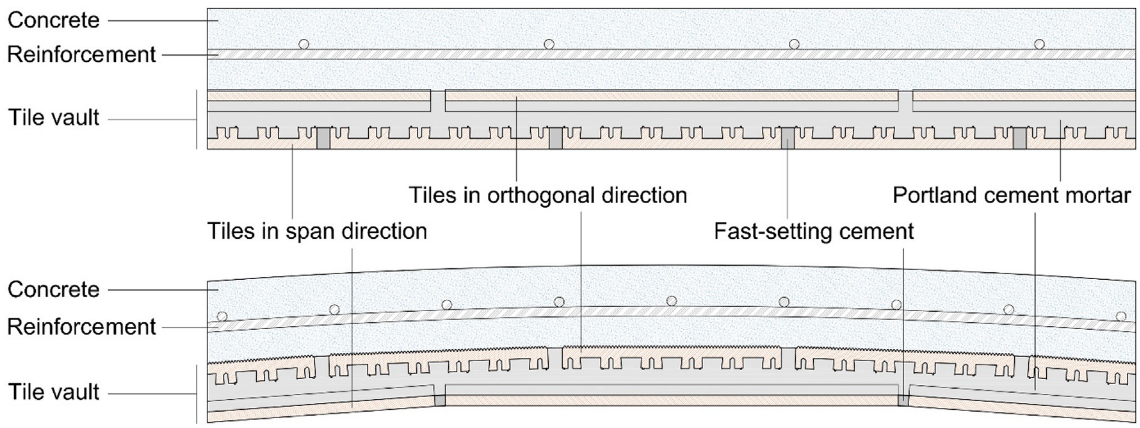

Fig. 2. Possible transversal and longitudinal cross-sections of the composite system. Featuring a two-layered tile vault and reinforced concrete [1].

For the construction technique proposed in this paper, once the tile vault is built "in space", i.e., without formwork, it is then used as formwork for the concrete. The shell does not suffer a high increase in its thickness, as the tile vault is structural and, at least, takes the dead load component of the shell. Compared to a typical tile vault with multiple (more than two) layers, the addition of a top layer of concrete to, for example, a two-layered tile vault reduces time and labour work thanks to the easier applicability of the concrete in comparison with the placing of the bricks. Compared to a typical concrete vault, this system reduces costs by allowing the construction without a formwork. Besides, it provides an exceptional finishing to the intrados. The reinforcement allows a minimum thickness and makes the system valid for long-span shells, which would probably be too massive and heavy otherwise. Furthermore, the addition of reinforcement allows the construction of expressive, free-form structures capable of resisting tensile stresses and bending moments, beyond the compression-only masonry restriction [6].

The first layer of the tile vault is the one requiring more specific materials. There are two main material requirements in order to build "in space": light bricks and fast-setting binder. Tiles (thin bricks) or hollow bricks can be used to satisfy the former requirement and fast-setting cement or gypsum are used to comply with the latter. Providing a quantitative range of the first layer bricks' admissible weight is not straightforward, as it is highly dependent, among others, on the brick's header and stretcher surfaces in contact with the fast-setting binder and on the quality of the mentioned binder. From the authors' experience, using a fast-setting cement similar to the one described in Section 3, and tiles with sizes around 280 mm $\times$ 140 mm and a minimum thickness of 14 mm, the brick's weight should not surpass 1.5 kg. It is also worth to mention that the ability of the mason plays an important role regarding this matter.

If the intrados of the composite system is to be left exposed, the selection of tiles and binder becomes also an aesthetical matter, in which colour, size, texture, pattern and execution quality turn into major decisions for the designer [8,18].

The bricks of the second and subsequent layers (if needed) should be laid staggered with the first layer's tiles, i.e., avoiding continuous joints through the section of the vault. Heavier bricks can be used in this case, as well as regular lime or Portland cement mortar. In some cases, mortar made of fast-setting cement and sand (proportion 1:2 or 1:3) has been traditionally used, adding some setting retardant to increase its workability [8].

Different options for the reinforcement can also be considered, such as, for example, steel bars, fibres, glass-fibre meshes, etc. The designer's decision regarding reinforcement will result in different material and structural properties, as demonstrated in this paper's experiments. Geometry also plays an important role in that decision, as some options are more difficult to apply on complex shapes (which implies more time and therefore higher costs). For instance, reinforcement made by steel bars can easily be applied on a ruled surface or on a singly-curved vault. However, the construction process becomes much more difficult on a free-form shell, on which, for example, a glass-fibre mesh could be more easily adapted.

The proportions of the concrete mix are also of great importance. A balanced relationship between low flowability and self-compaction should be sought in order to allow the application of the concrete on steep surfaces while avoiding the need of intense vibration on the masonry vault.

Once the concrete hardens, the system becomes a composite structure. The composite structural behaviour can only be guaranteed if there is enough bond between the tile vault and the concrete. Until further research on the tile-concrete bond strength is carried out, the available research on masonry bond can already give hints about the strategies to improve the structural performance of the proposed composite technique in this regard. The available literature concludes that the brick–mortar bond is purely mechanical in nature [19,20] and identifies some key factors influencing masonry bond, namely the type of mortar (composition, water retention, workability, air content and setting characteristics), the type of masonry unit (material, moisture content, surface texture and absorption characteristics) and environmental factors such as curing conditions or workmanship (mainly the degree of pressure applied to the mortar and the masonry unit and the appropriate filling of the frog or valleys of the unit's surface) [21–23].

Regarding cement mortars, flexural bond strength increases with a higher amount of cement in the mix design and with higher values of the mortar strength [24]. The addition of lime or soil to the mix also improves the mortar's bond strength [20,24,25].

With respect to the masonry unit, the moisture content at the time of laying is a major factor influencing the bond strength. Partly wetted bricks show much better results in bond development than dry or completely saturated bricks [20,24–26]. The surface texture of the brick plays a role on the bond strength as well. Bricks with a bigger frog area on its surface present better bond performance [25,27].

3. Material characterization

As described in the previous section, there are different options regarding the materials composing the proposed structural system.

The reasons for the election of the specific materials for both samples and prototypes are described in this section along with the tests and results of the material characterization.

3.1. Masonry: Tiles, fast-setting cement and mortar

The tile vault is made of different materials that work altogether. Tiles were chosen for the first layer due to its reduced thickness and weight. The tiles had sizes of 277 × 134 × 14 mm, a weight of 800 g, were smooth on the face left exposed at the intrados and grooved on the face that would receive the mortar and the next layer of bricks. The binder for the first layer of tiles was a natural fast-setting cement. Although the experimental tests and the construction of samples and prototypes were all carried out in a laboratory-controlled environment, cement was chosen over gypsum due to its better resistance against moisture and water, envisaging the application of this technique outdoors.

A dry (already mixed) Portland cement mortar (M7.5) was used for the second and last thin tile layer and for the joint between the two thin tile layers. Tiles were also the best option for this second layer in order to minimize the thickness of the tile vault. Nevertheless, this layer used a slight different ones compared to first layer. The only difference lied on the smooth face of the first layer's tiles, which, in this case, had a small striped relief to improve its connection with the concrete.

Compression and bending tests were carried out on the materials composing the tile vault, namely tiles, fast-setting cement and mortar. The extruded industrial tiles were grooved and striped in one direction, presenting an orthotropic behaviour. Besides, in the built prototypes, as traditionally done, tiles were placed in two different directions (Fig. 2). For the barrel vaults, the direction of the extrusion corresponded to the span direction for the first layer and the orthogonal direction for the second. Therefore, four compression tests in each of these two directions were performed (Fig. 3). In order to avoid buckling due to the slenderness of the pieces, two tiles were tested simultaneously, glued together by a mortar join. The specimens to be tested in the extrusion direction had sizes of 145 × 134 × 36 mm (Fig. 3, left) and the ones to be tested in the orthogonal direction had sizes of 131 × 136 × 36 mm (Fig. 3, right). The tests demonstrated a much superior stiffness of the bricks compared to that of the mortar, with the tiles showing major brittle failures and the mortar remaining apparently almost unaffected. The authors assumed that the big majority of the load was hence supported by the tiles and only a negligible part by the mortar. Results of the compressive strength were 111 N/mm^2 for the tiles in the extrusion direction and 87 N/mm^2 for the orthogonal ones, with coefficients of variation of 8.93% and 2.70% respectively.

The natural fast-setting cement and the Portland cement mortar were tested in bending and compression according to EN 1015 [28]. The ratio water/cement of the fast-setting cement was 0.5 and its average flexural strength was 0.9 N/mm^2, with a coefficient of variation of 1.48%. The average flexural strength of the mortar was 2.5 N/mm^2, with a coefficient of variation of 8.47%. The average results and coefficient of variation for the compression tests of the fast-setting cement were 4.47 N/mm^2 and 10.16%, whereas for the Portland cement mortar were 6.98 N/mm^2 and 14.72%. The specific weight of the cement was 1373 kg/m^3 and that of the mortar was 1940 kg/m^3.

3.2. Concrete and steel

The mixture for the concrete was obtained following the well-known Bolomey's curve seeking to achieve an optimal packaging of the mineral skeleton in order to generate the required properties without using high quantities of cement. The proportioning of the concrete mixture was as follows: for 1 kg of cement, 2.877 kg of sand, 2.324 kg of gravel, 0.332 kg of filler, 0.5 kg of water and 0.01 kg of super-plasticizer. The cement was Portland cement CEM I 42.5 N-SR 5 (EN 197–1) [29]. The diameter of the aggregates was less than 4 mm for the sand and between 5 and 12 mm for the gravel. Limestone filler was used to contribute to an adequate flowability and to improve cohesion by increasing the aggregate's specific surface. Proportion water/cement was 0.5 and super-plasticizer (MasterGlenium ACE425, BASF) was added in an amount of 1% of the cement's weight to increase workability without generating segregation problems. The resulting concrete had a specific weight of 2460 kg/m^3.

The concrete in each pair of equal load tests (two composite barrel vaults and two steel-reinforced composite barrel vaults) was different due to the need to use a different provider of the sand and gravel. During the prototype's construction, concrete samples

Fig. 3. Compression tests on tiles. Left) extrusion direction, right) orthogonal direction.

were taken in order to obtain its strength in the two kinds of prototypes. The moulds used to produce these samples were the ones available at the laboratory at each specific moment, namely, 100-mm-diameter, 200-mm-high cylinders or 100-mm-edge, cubic moulds. The samples and tests were fabricated and performed according to EN 12,390 [30].

Seeking a reduction of the concrete mix segregation and prevention of cracking during construction, polypropylene fibres were added to the concrete in the first set of tested composite vaults. Construction was easier than in the following two prototypes since the placement of the steel bars was avoided. The fibres had a length of 45 mm, a cross section surface of 0.636 mm^2 and a specific weight of 910 kg/m^3. They were added to the concrete mixture in a proportion of 0.024 kg for 1 kg of cement. Five 100-mm-diameter, 200-mm-high cylinders of this concrete were tested in compression with results of 38.56 N/mm^2 for the compressive strength and a coefficient of variation of 5.74%.

With respect to the second set of composite vaults, steel reinforcement rods were used. The simple geometry of the barrel vaults guaranteed an easy placement of the rebars. From the steel-reinforced composite barrel vaults' concrete, ten 100-mm-edge, cubic samples were tested in compression, resulting in a mean value $f_{c,cube}$ equal to 27.75 N/mm^2 and a coefficient of variation of 4.41%. A factor of 0.8 was used to convert the average compressive strength of cubic samples to a 150 mm diameter by 300 mm high cylindrical samples (as documented in Eurocode 2 [31]). The result is a concrete compressive strength of f_c equal to 22.20 N/mm^2.

The diameter of the steel bars needs to be considered regarding the process of construction. Thick steel bars are difficult to bend and thus difficult to place on the vault. The chosen diameter was 6 mm, which allowed an easy construction. Ten 6-mm diameter steel reinforcement bars were tested in tension according to EN ISO 15630–1 [32]. The mean tensile strength was equal to 581 N/mm^2 and the Young's Modulus was equal to 207000 N/mm^2 with coefficients of variation of 0.95% and 3.61% respectively.

4. Load tests on tile-concrete composite barrel vaults

This section describes the setup, monitoring and results of the load tests on two composite structures consisting of a tile barrel vault as integrated formwork for concrete. In the next sections, these two prototypes are also referred as composite (barrel) vaults 1 and 2.

4.1. Vault's geometry and test configuration

The cylindrical tile-concrete composite barrel vaults had a span of 2.78 m, a rise of 0.25 m and a width of 1 m. They were composed of a 36-mm-thick tile vault and a 50-mm-thick concrete layer with polypropylene fibres (Fig. 4). The composition and properties of the materials used in the construction of the prototypes are described in Section 3.

The setup of the load test and the monitoring system is presented in Fig. 5. During the tests the supports were pinned (able to rotate), with translation partially constrained by means of tension ties, whose stiffness would allow small deformations during the load test. Only one of the two supports was therefore stiffly anchored to the fixed, loading steel frame and the horizontal displacement of the opposite one was measured by means of two LVDTs.

The hinges at the supports were blocked (not allowed to rotate) during construction, so that the vaults could have been built in the traditional way, i.e. without the need of a formwork, except at one of its boundaries (only required for the first row of bricks to form the first arch/stable section).

The load was applied at ¼ of the span on a concrete surface, rectangular in plan, 115 mm long in the direction of the span and occupying the entire width of the vault (Fig. 5 and Fig. 6). A single actuator applied a punctual load that was distributed on the entire surface of the loading platform through a HEA 140 steel profile. The load was displacement-controlled at a constant speed of 0.1 mm/min until failure. The loading device was a hydraulic quasi-static HIDRASA actuator of 250 kN of force range and 500 mm of displacement range.

In addition to the load and displacement values measured by the actuator, monitoring consisted of eight potentiometers measuring vertical displacements in different spots over the vaults and two LVDTs measuring horizontal displacements at the two sides of one support (Fig. 5 and Fig. 6). The potentiometers had a 100 mm range and 0.2% linearity, while the inductive LVDTs had a 20 mm range and 0,2% linearity (type HBM WA 20). These displacement sensors were intended to clarify the overall deformation of the vault and to identify uneven behaviour on opposed edges. The potentiometers were placed at the quarters and at the middle of the span: three at each quarter-span position (one at each edge and one in the central position) and two at the mid-span position (one at each edge). Additionally, two load-cells were installed at both tension ties to measure the horizontal thrust.

Fig. 4. Construction of the tile-concrete composite barrel vaults.

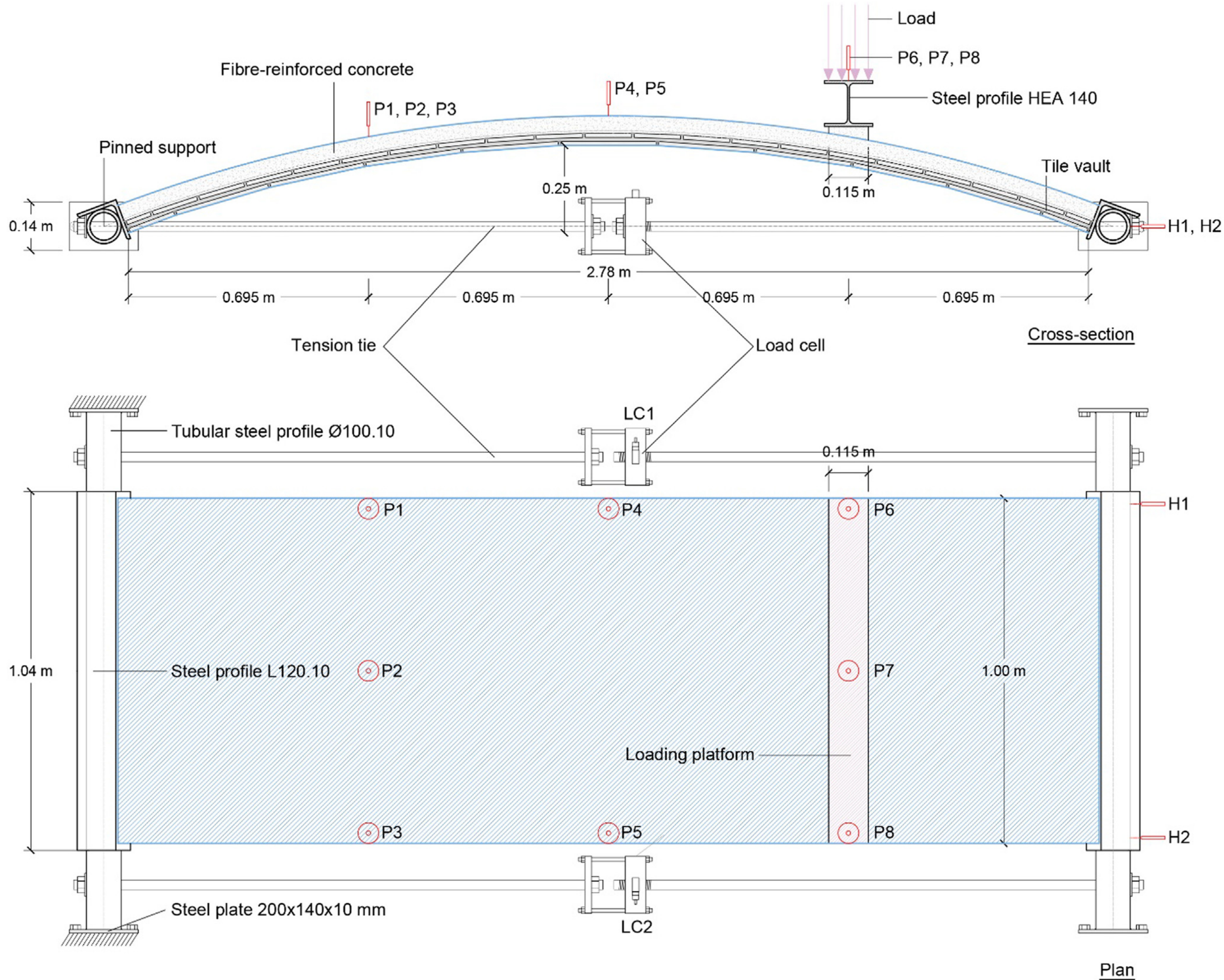

Fig. 5. Setup of the monitoring and load test for the tile-concrete composite barrel vaults. Potentiometers indicated as P1 to P8, LVDTs indicated as H1 and H2 and load-cells indicated as LC1 and LC2. Up) cross section, down) plan.

Fig. 6. Load test setup of the tile-concrete composite vaults.

The two vaults (5.7 m^2 in total) were built in one and a half working days by two expert masons and one workman.

4.2. Results and discussion

The ultimate loads of the two tested vaults were 25.31 kN and 27.17 kN for composite vault 1 and 2 respectively, resulting in an average ultimate load of 26.24 kN (Fig. 7), far higher than required in Eurocode 1 [33] as imposed concentrated loads on floors, balconies and stairs in buildings with category of use A, B, C and D, where the highest recommended value intended for determination of local effects is 7 kN. These categories of use include areas for domestic and residential activities, office areas, areas where people may congregate and shopping areas [33].

The two vaults had a brittle behaviour evinced by the graphic in Fig. 7, which shows the load–displacement curves of the two tile-concrete composite barrel vaults at the loading point. The load–displacement curves' drops have a direct correspondence with the sudden formation of the two hinges, clearly identified during the load tests. The failure mechanism, featuring the two expected hinges, is shown in Fig. 8. The cracking pattern of both vaults is indicated in Fig. 9. The first hinge revealed itself as growing cracks at the intrados under the load line or slightly shifted to the nearest support. In the case of composite vault 1, a single crack was located at around 80 mm from the loading platform's edge in the direction of the closest support following a straight path through the width of the vault cutting the masonry pieces (not following the joints' pattern) (Fig. 10). In the case of the composite vault 2, two cracks

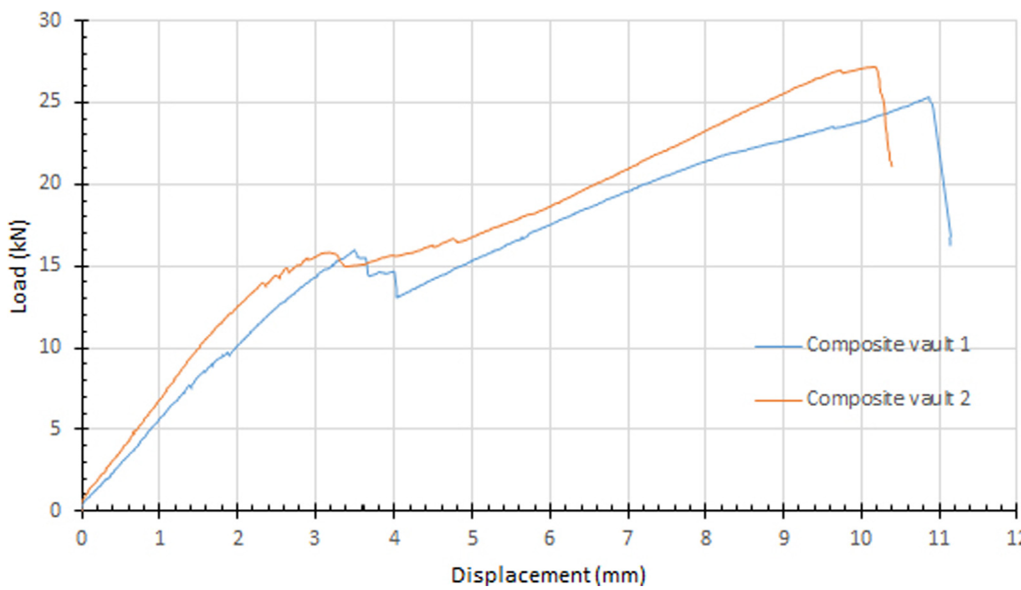

Fig. 7. Ultimate load test. Load-displacement curves of the two tile-concrete composite barrel vaults at the loading point (P7, Fig. 5).

Fig. 8. Composite vault 1 showing two hinges and its failure mechanism.

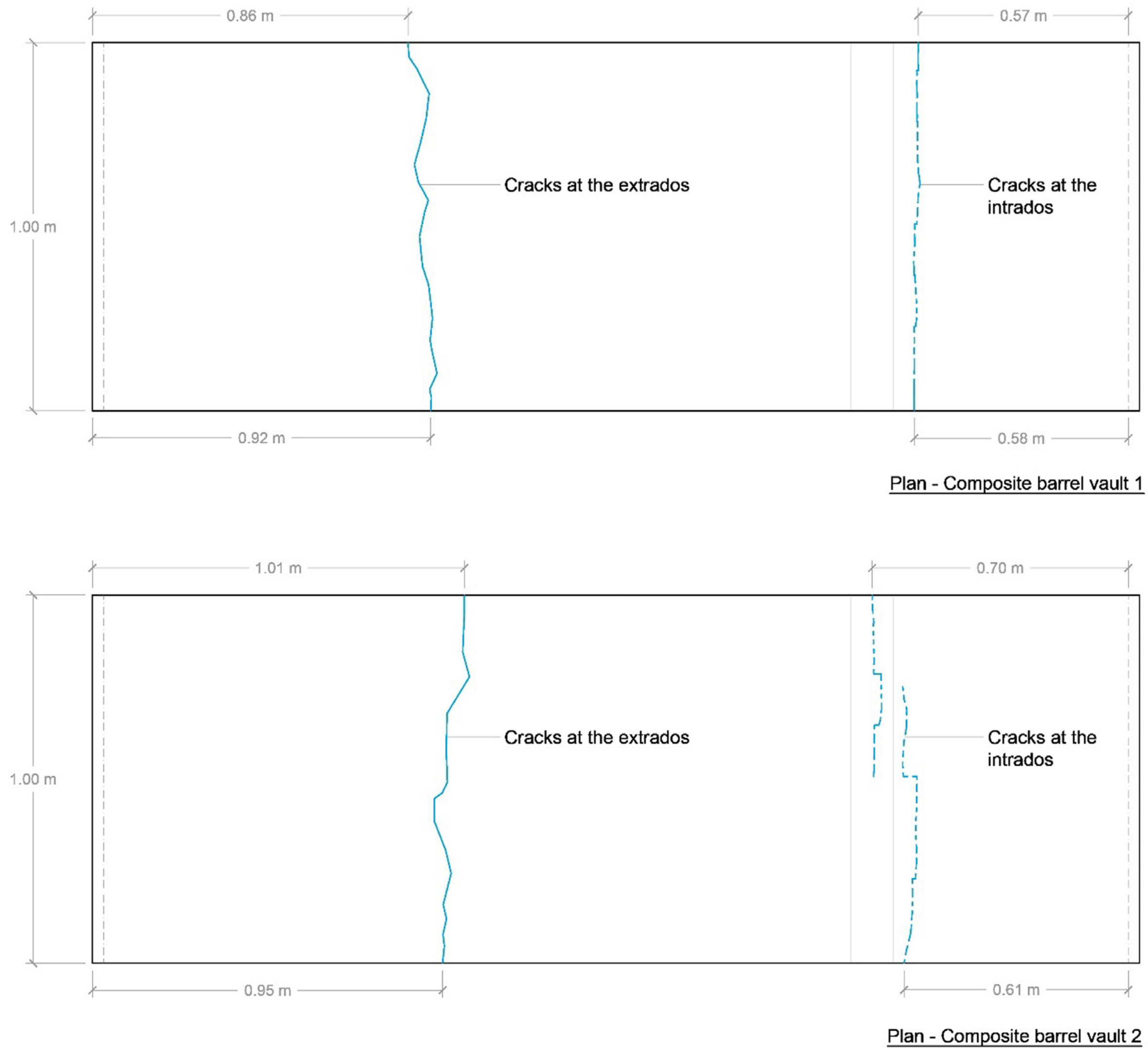

Fig. 9. Cracking pattern of the composite barrel vaults 1 and 2.

related to the first hinge were reported: one under the load line from one edge to approximately half of the vault's width, and the other one slightly shifted towards the closest support, from the opposite edge to approximately three quarters of the vault's width (Fig. 11). A crack at the extrados of the opposite side of the load line formed the second hinge (Fig. 12).

The two composite vaults showed also similar results when comparing the data from the rest of the potentiometers measuring vertical displacements (Fig. 13 and Fig. 14). As expected, the three potentiometers in the load line (P6, P7 and P8) registered the biggest displacements, whereas potentiometers P1, P2 and P3 measured the smallest displacements, which were around 1 mm after the formation of the first hinge (the first sudden drop in the curves, at around a load of 16 kN in both vaults) and before the peak load. The formation of the second hinge at the peak load comes together with a loss of load-bearing capacity and a sudden upwards displacement measured by potentiometers P1 to P5 (Fig. 13 and Fig. 14).

Since the formation of each hinge produces a sudden decrease on the load, these drops are also noticeable in the load-horizontal displacement curves (Fig. 15 and Fig. 16) and in the load-horizontal thrust curves (Fig. 17 and Fig. 18). The horizontal displacement measured by the LVDT H1 in composite vault 1 (Fig. 15) did not measure properly after displacement 0,96 mm due to a technical limitation; these data are therefore not shown in the corresponding graph. The data measured by the LVDTs and the load-cells are also similar comparing both vaults and without significant uneven displacements between the opposed edges. The maximum horizontal displacement coincides with the peak load in both tested structures and is equal to 1.25 mm and 1.54 mm in the first and the second composite vaults, respectively. The maximum registered horizontal thrusts in composite vault 1 were 24.66 kN (LC1) and 22.35 kN (LC2) (Fig. 17), whereas for vault 2 they were 23.17 kN (LC1) and 25.49 kN (LC2) (Fig. 18).

4.3. Comparison with an unreinforced tile vault

A load-test setup similar to the one described above was applied to plain, unreinforced, tile vaults (Fig. 19) [34]. The tested structures were two cylindrical, 36-mm-thick, tile barrel vaults with a span of 2.80 m, a rise of 0.26 m and a width of 1 m; i.e., in comparison with the composite vaults 1 and 2, these new tile vaults could be considered as the result of eliminating the concrete and shifting them slightly upwards to make their middle surface coincide with the axis of the steel profiles that support the structure. The geometry of the vaults, the setup of the load test and the monitoring system is presented in Fig. 20. The loading device,

Fig. 10. Crack on the intrados of the composite barrel vault 1 showing the formation of the first hinge.

Fig. 11. Cracks on the intrados of the composite barrel vault 2 showing the formation of the first hinge.

the potentiometer and the LVDTs were the same ones as in the first set of load tests.

The ultimate loads of the two tested tile vaults were 4.32 kN and 4.69 kN, resulting in an average ultimate load of 4.51 kN. Compared to the studied composite vaults, the addition of a 50-mm-thick concrete layer to the 36-mm-thick, 2.80-m-span, tile vault resulted in an increase of 482% of the loading capacity.

Damage in masonry vaults is frequently associated to relative displacements of the abutments, which compromise the vault's stability [35–37]. The proposed composite structure provides as well extra displacement capacity with respect to the plain tile vault. The average horizontal displacements at the peak load from LVDTs H1 and H2 (Fig. 20) in the two unreinforced masonry vaults were 0,45 mm and 0,54 mm. The horizontal displacements at the peak load measured during the tests of the composite vaults were 178% higher than those of the tile vaults, which shows a substantial improvement of the structural performance regarding the abutments' displacement capacity.

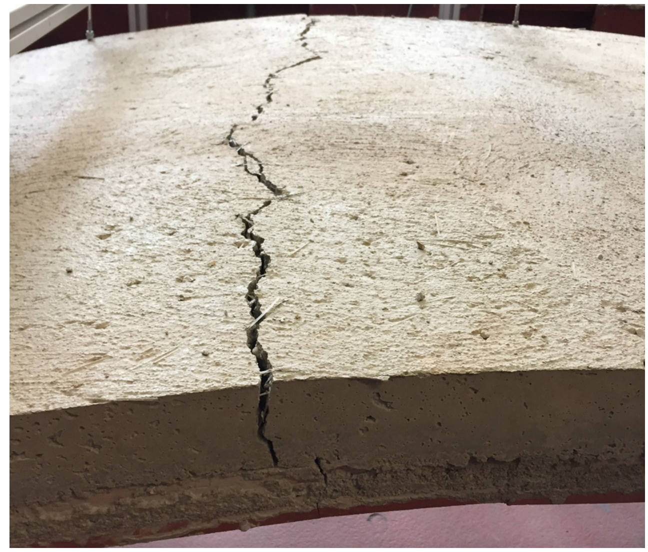

Fig. 12. Crack on the extrados of the composite barrel vault 2 showing the formation of the second hinge.

Future work on the proposed construction technique will include further numerical and experimental research to better understand and quantify the additional abutments' displacement capacity provided by the concrete layer.

5. Load tests on steel-reinforced composite barrel vaults

This section describes the setup, monitoring and results of the load tests on two steel rod-reinforced composite barrel vaults. In the next sections, these vaults are also referred as composite (barrel) vaults 3 and 4.

5.1. Vault's geometry and test configuration

The cylindrical steel-reinforced barrel vaults tested had the same geometry of the ones presented in the previous section: a span of 2.78 m, a rise of 0.25 m and a width of 1 m. They were composed of a 36-mm-thick tile vault and a 50-mm-thick concrete layer. The composition and properties of the materials used in the construction of the prototypes are described in Section 3. The reinforcement was placed at the central part of the concrete layer and consisted of 6-mm-diameter steel bars at 70 mm in both directions. As mentioned in Section 3.2, the diameter of the steel reinforcement bars was chosen, among those available in the market, as the one that could best allow an easy construction regarding their bending and placement, not only in the case of the built barrel vaults, but also envisaging the eventual construction of more complex shapes. The spacing of the bars was decided as one with a high steel quantity, but such that the concrete could be placed and compacted satisfactorily. Different options for the reinforcement amount and its influence in the structural behaviour of the tested vaults are discussed in Section 6.

During the tests the supports were pinned (able to rotate), with translation constrained by means of stiff ties, namely, two steel

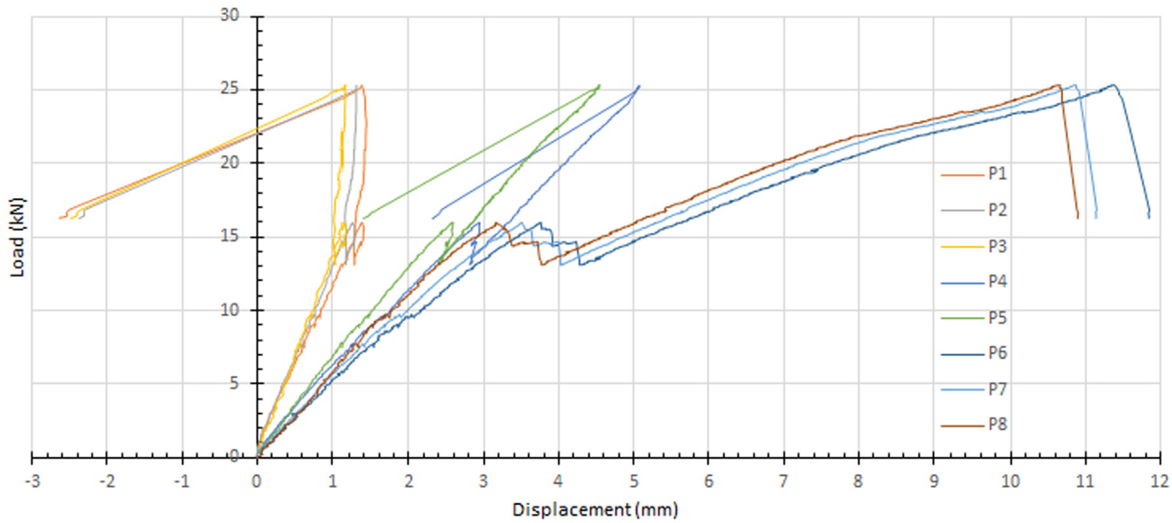

Fig. 13. Load-displacement curves of the composite barrel vault 1.

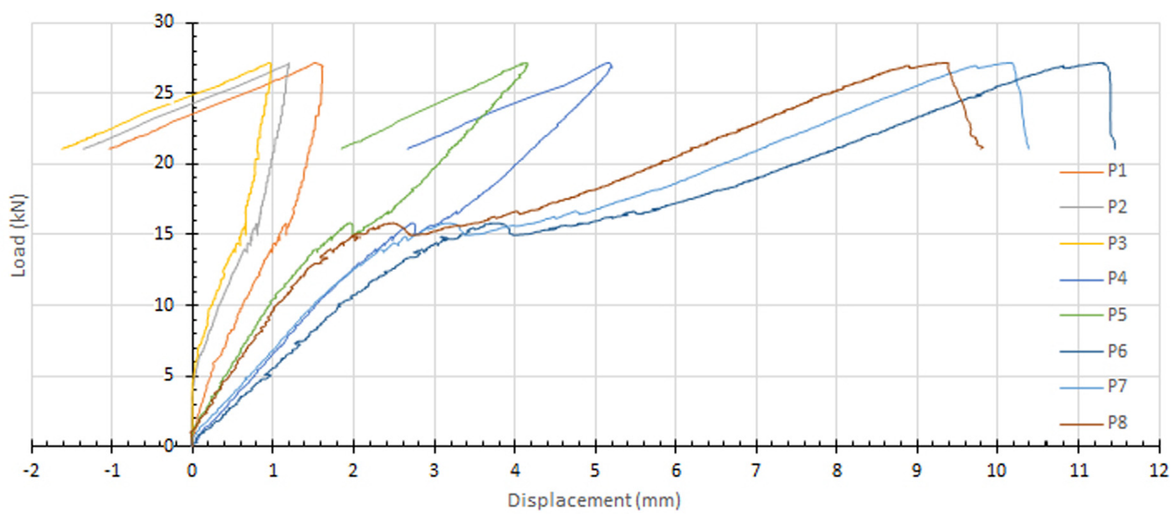

Fig. 14. Load-displacement curves of the composite barrel vault 2.

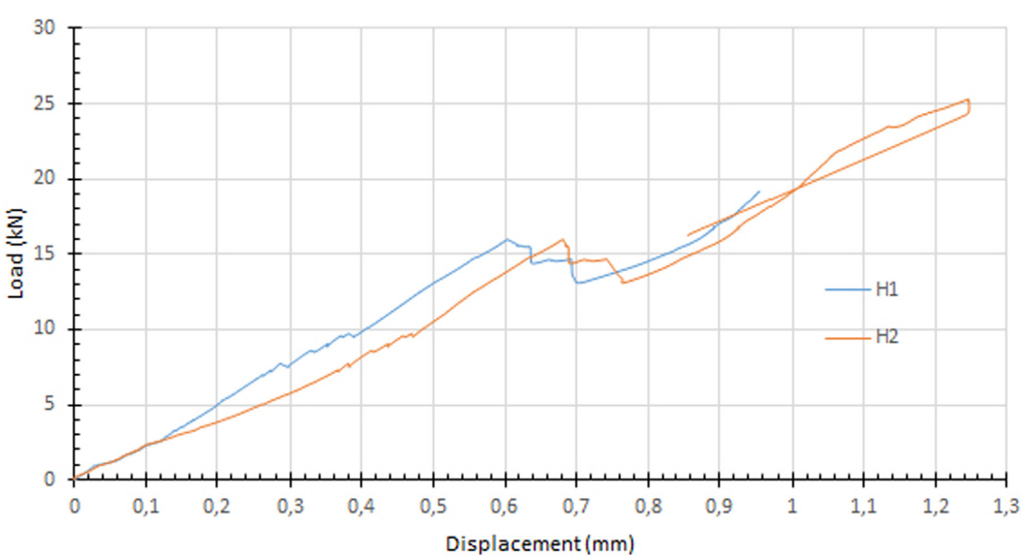

Fig. 15. Load-horizontal displacement curves of the composite barrel vault 1.

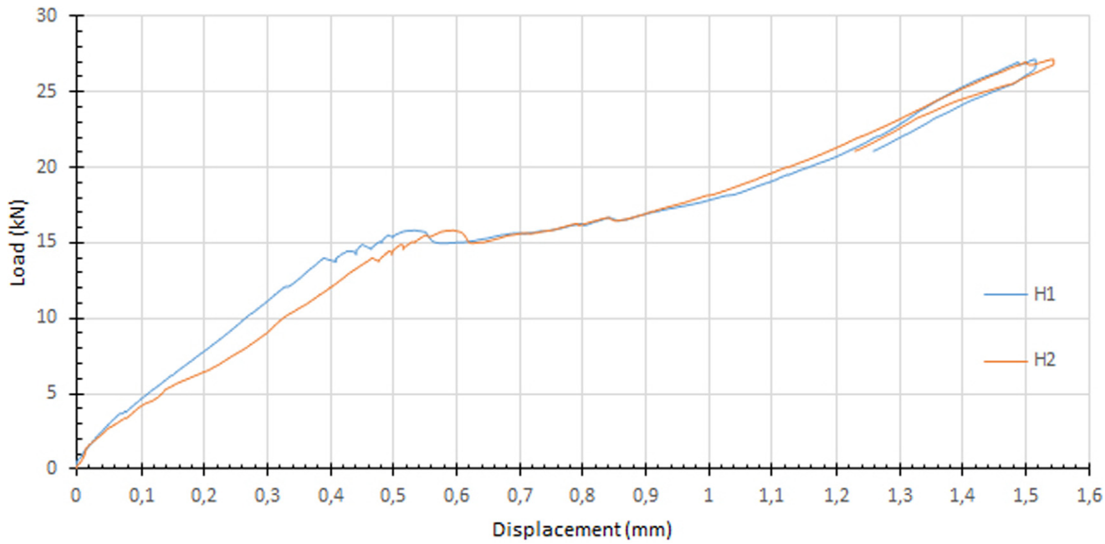

Fig. 16. Load-horizontal displacement curves of the composite barrel vault 2.

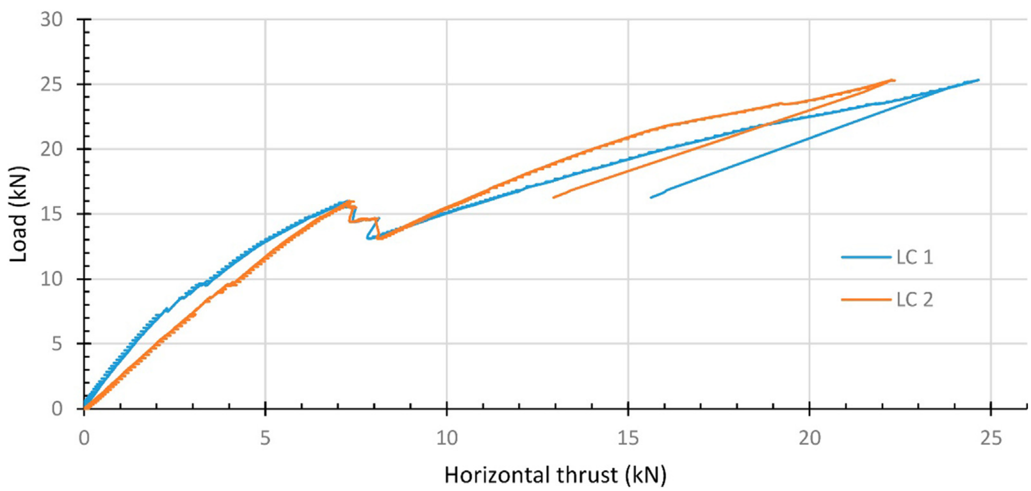

Fig. 17. Load-horizontal thrust curves of the composite barrel vault 1.

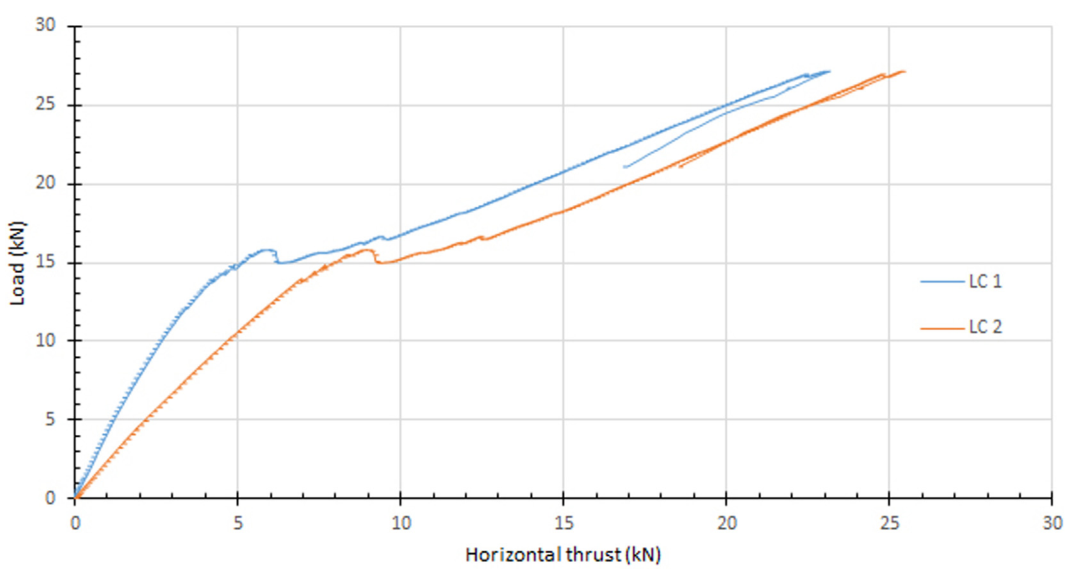

Fig. 18. Load-horizontal thrust curves of the composite barrel vault 2.

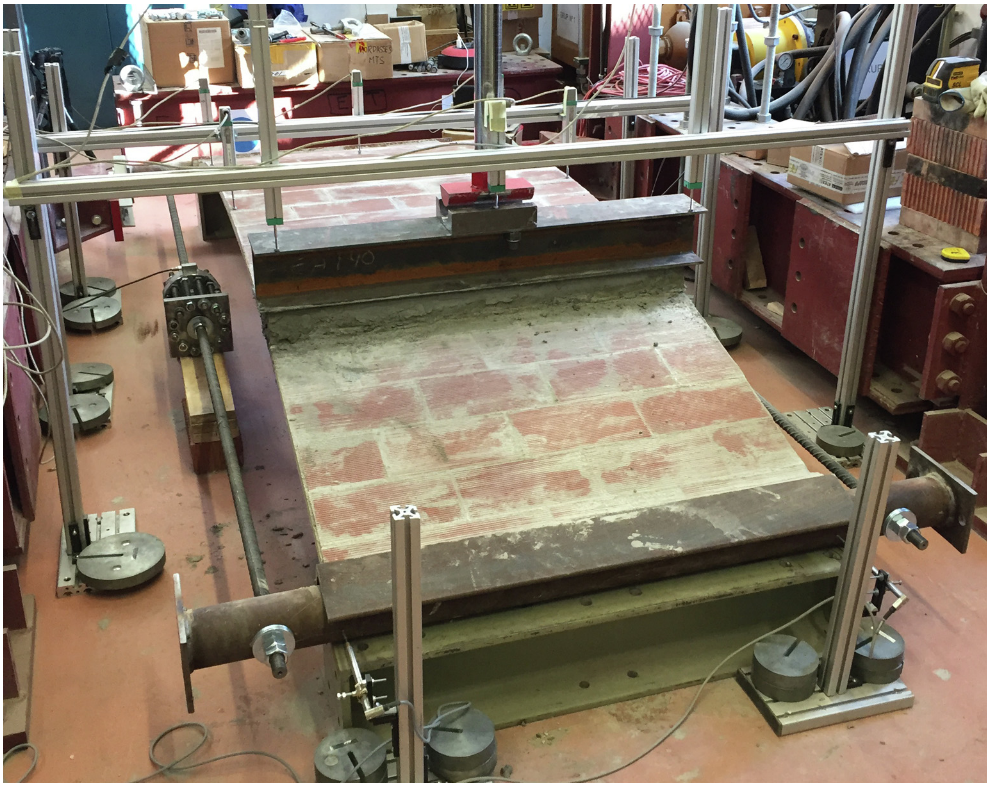

Fig. 19. Load test setup of the plain, unreinforced, tile vaults.

profiles UPN 140. These ties were part of a steel frame on which the vaults were built to allow transportation without any displacements of the supports. The tension ties and load-cells used in the first set of experiments were substituted by the two UPN 140 steel profiles, which were stiffly anchored to the fixed, bigger, loading steel frame in order to avoid any possible displacement of the vault or vault's supports during the load application process. These displacements would have complicated the structural assessment using limit analysis-based methods.

The loading device and the potentiometers were the same ones as in the first set of load tests. The same setup and monitoring system were applied as well (Fig. 21). Expecting a higher peak load and ductile response, the constant loading speed was increased to 0.4 mm/min in order to reduce the duration of the tests.

The two vaults (5.7 m^2 in total) were built in two working days by two expert masons and one workman. During the first day the tile vaults were finished and the reinforcement placed. The second day was devoted to the concrete works, building the loading platforms and casting the samples.

5.2. Results and discussion

The two vaults had a non-linear behaviour with similar ultimate loads (52.43 and 53.15 kN) (Fig. 22), again in this case, far higher than required in Eurocode 1 [33] for the imposed concentrated loads, type of structure and categories of use mentioned in Section 4.2.

Both vaults, whose cracking pattern is indicated in Fig. 23, developed the same failure mechanism with the formation of two hinges. A growing crack at the intrados under the load line through the entire cross-section and occupying the whole width of the vault made the creation of a first hinge evident (Fig. 24) and cracks at the extrados of the opposite side of the vault formed the second one (Fig. 25). In both vaults the second hinge did not reveal itself as a single crack, but as a group of cracks occupying the entire width of the vault and spreading along a portion of the vault's length.

Both vaults featured a sudden debonding between the tile vault and the concrete layer, which meant the end of the tests (Fig. 26). Fig. 22 shows the load–displacement curves of both vaults at the loading point (P7, Fig. 21). In vault 3, debonding occurred immediately after the generation of the second hinge and prevented the development of a post-peak unloading branch. The match of the two plots at the first stretch in Fig. 21 and the almost null stiffness reached around the peak load (note the slopes' horizontality of the load–displacement curves), along with the observed cracks at the extrados of the vault (Fig. 25), confirm that debonding occurred either simultaneously or right after the generation of the second hinge, linked to the excessive deformation due to the formation of the mechanism. In vault 4, debonding occurred far beyond the peak load.

The displacements registered by the two vault's potentiometers, up to the peak load, were very similar. Fig. 27 and Fig. 28 show the load–displacement curves of the steel-reinforced composite vaults obtained with the eight vertical displacement sensors. As expected, the potentiometers measuring the vertical displacements at the three points of the line where the load was applied registered the biggest displacements, reaching at the peak load 29 mm and 32 mm at P7 for the vaults 3 and 4 respectively. The smallest displacements were reported at the quarter-span, opposite side of the load (points P1, P2 and P3). The registered data at three measured points at that line revealed positive (downwards) displacement at a first stage. A gradual loss of stiffness of the vault slows down those displacements until the three points start then

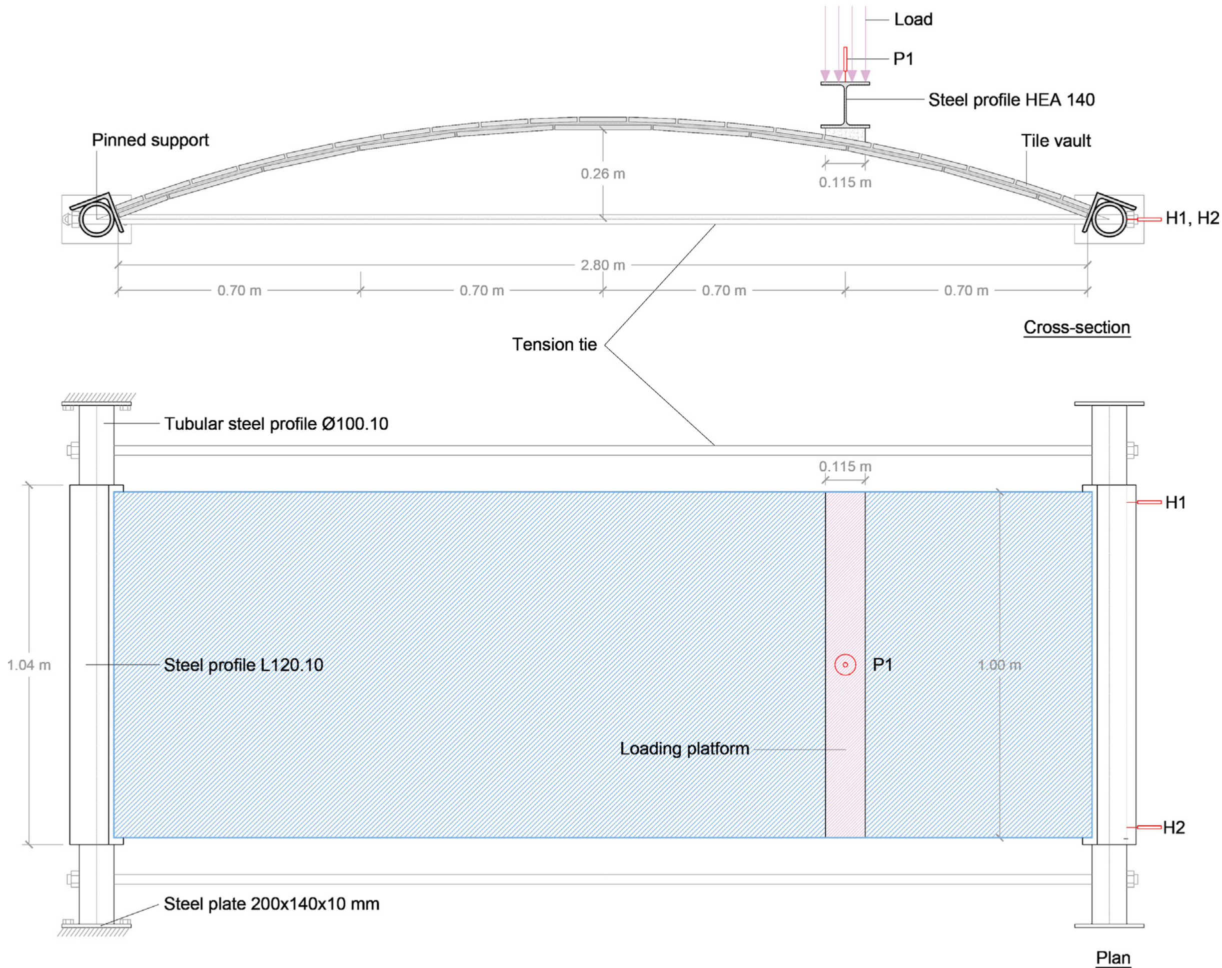

Fig. 20. Setup of the monitoring and load test for the plain, unreinforced, tile vaults. Potentiometer indicated as P1, LVDTs indicated as H1 and H2. Up) cross section, down) plan.

moving back upwards coinciding approximately with the peak load and the total loss of stiffness.

Load-displacement curves of both vaults do not show significant uneven displacements between the opposed edges in the same measured line.

6. Structural analysis

The presented combination of masonry and steel-rod reinforced concrete creates a new type of composite structure that needs experimental validation and new calculation methods and models to deal with the specific features of the system. The Extended Limit Analysis of Reinforced Masonry (ELARM), recently presented in [1] and [6], is a method for the structural design and analysis of such steel-reinforced concrete, tile-vaulted structures. ELARM is based on limit analysis, but takes into account the tensile capacity of the reinforcement and the finite compressive strength of the tile vault and concrete by virtually increasing the thickness of the structure accordingly and providing graphical and intuitive results. The composite cross-section is analysed to obtain its maximum negative and positive moment for the corresponding axial load. The upper and lower limits of the vault's virtual thickness are defined by the maximum possible eccentricity related to the positive or negative moments, respectively. The calculation of the eccentricities, moments and axial forces is done in the specific cross-sections resulting from the division of the analysed structure in virtual voussoirs. ELARM is suitable for reinforced composite (concrete and/or masonry) arched structures with sufficient ductility to create the required number of hinges to develop a failure mode corresponding to a plastic mechanism [1].

ELARM was used for the assessment of the steel-reinforced composite prototypes, namely, vaults 3 and 4. The geometry of the vaults and the material properties were introduced into the computational model to apply the uniqueness theorem (Fig. 29) and compare the results with those obtained in the experimental tests. The values of the concrete's specific weight and compressive strength, the steel's tensile strength and Young's modulus and the tile vault's specific weight introduced in the model were the ones described in section 3. Using the material properties of the binders and the masonry units as described in [1] and documented in Eurocode 6 [38], the compressive strength of the tile vault was estimated as 13.45 N/mm^2 for a corrected thickness of 33.6 mm, which results from considering the slight tile vault's thickness variation due to its faceted geometry built with straight masonry units [1].

ELARM predicted satisfactorily the ultimate load and the collapse mechanism (Fig. 29 and Fig. 30). The average of the two peak loads obtained experimentally was 52.8 kN, whereas ELARM's predicted ultimate load was 53.6 kN, only 1.5% higher [1].

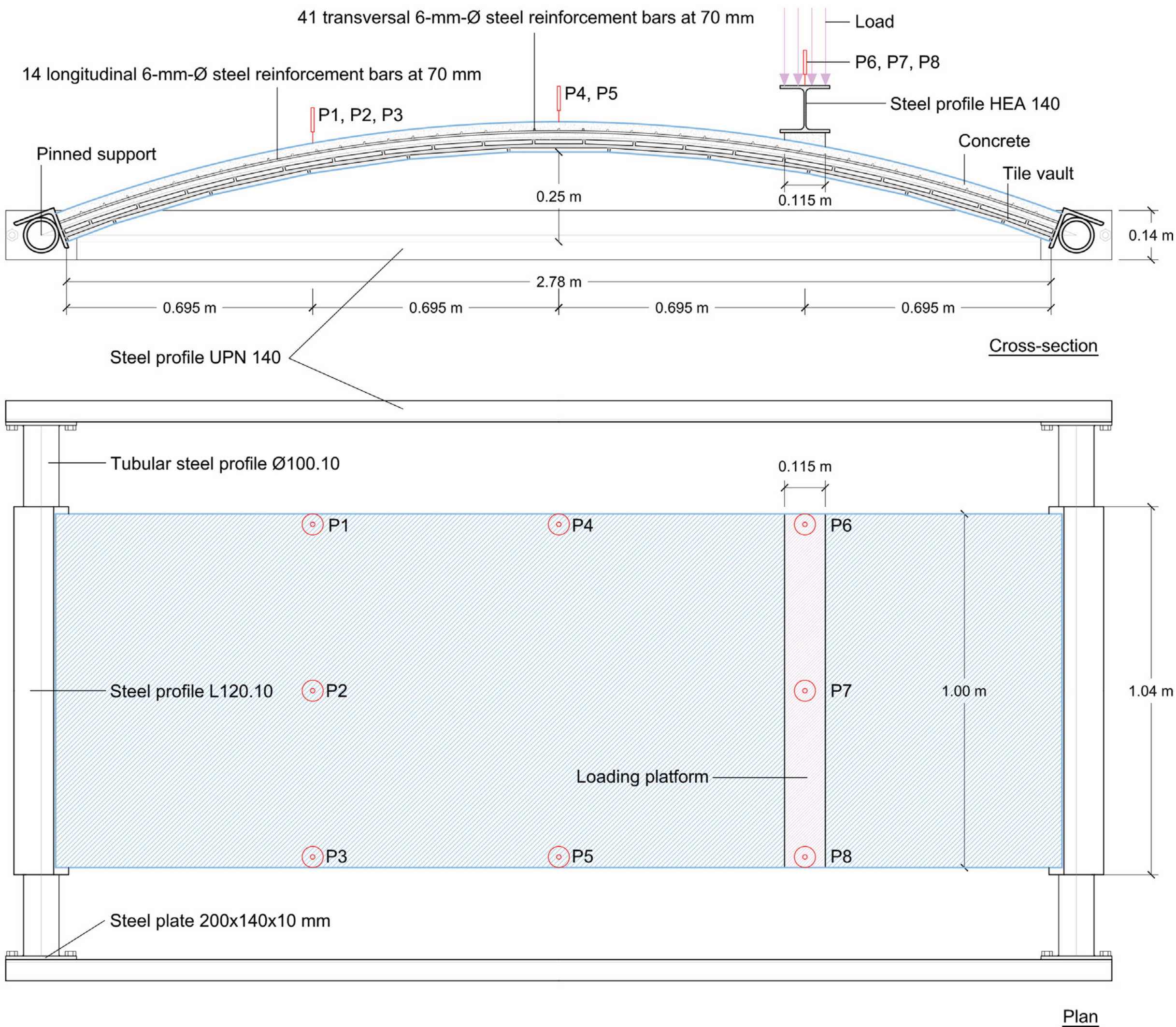

Fig. 21. Setup of the monitoring and load test for the steel-reinforced composite barrel vaults. Potentiometers indicated as P1 to P8. Up) cross-section, down) plan.

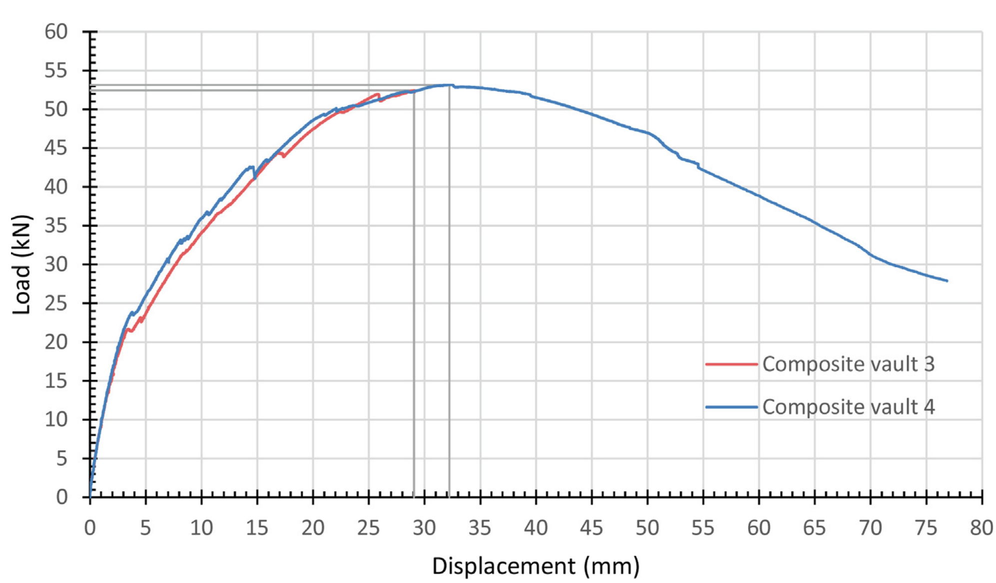

Fig. 22. Ultimate load test. Load-displacement curves of the composite barrel vaults 3 and 4 at the loading point (P7, Fig. 21).

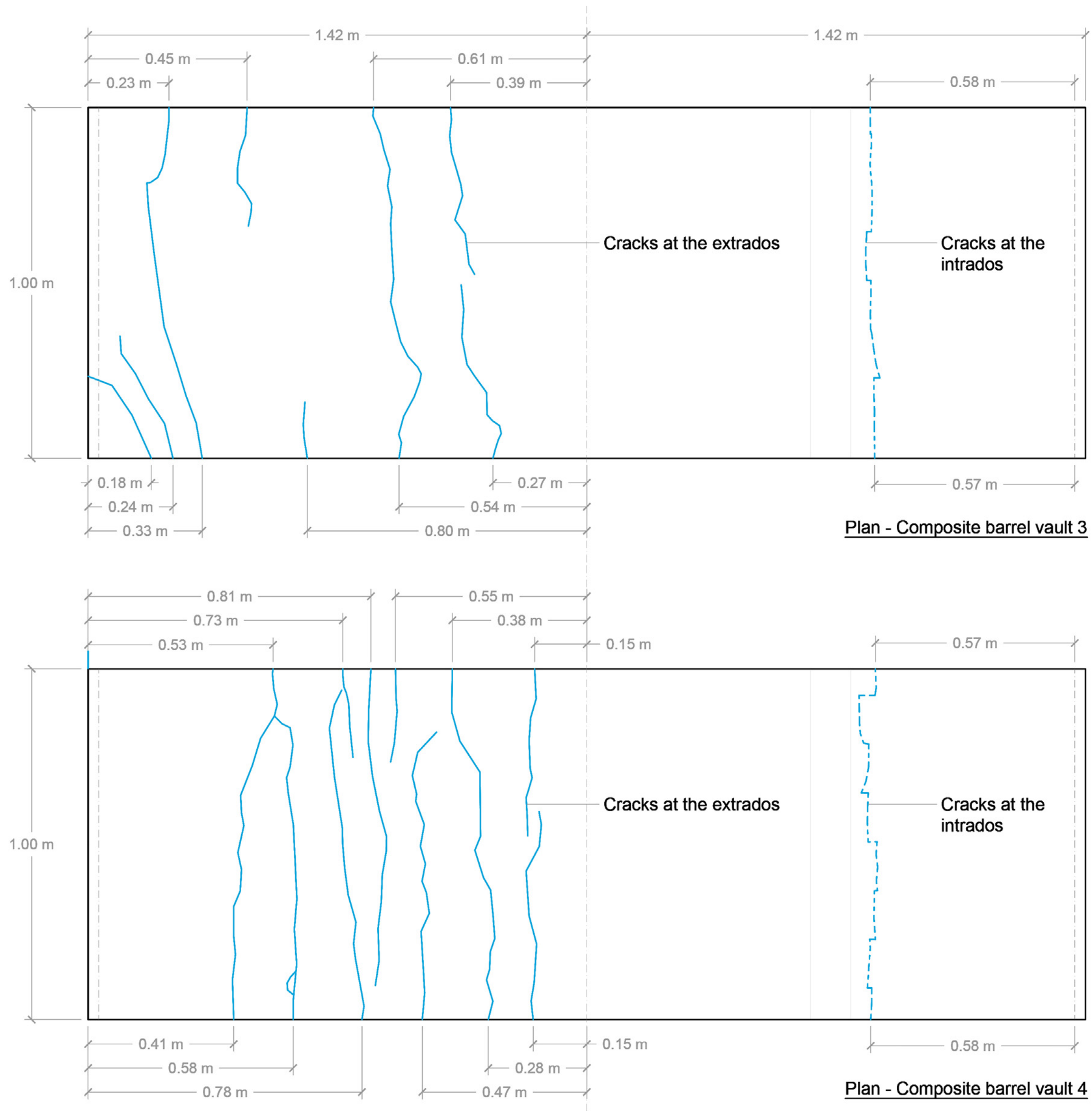

Fig. 23. Cracking pattern of the steel-reinforced composite barrel vaults 3 and 4.

The cross-sectional analysis carried out with ELARM showed failure occurring with concrete at its ultimate strain and steel not yielded for the positive moment (at the first hinge, under the applied load), and tile vault at its ultimate strain and steel yielded for the negative moment (at the second hinge) (Fig. 30).

ELARM allows the study of the ultimate strain state of the materials in the cross sections corresponding to the joints of the fictitious voussoirs along the length of the vault. This permits the design of the reinforcement scheme to obtain a ductile structure avoiding over-reinforced vaults and brittle behaviour. A parametric study on the amount of reinforcement in the tested barrel vaults showed the ultimate loads and strain state of the cross sections at the two hinges for the different reinforcement options. Taking the reinforcement scheme of the studied vaults as starting point, featuring fourteen 6-mm-diameter steel bars distributed along the width of the vault and with a total steel area of 395.8 mm^2, the reinforcement amount was gradually modified by adding or removing one steel bar (28.3 mm^2). The addition of one bar to the tested scheme resulted in an increase of the ultimate load from 53.6 to 58.4 kN and in a shift of the cross section's strain domain for the negative moment, with tile vault at its ultimate strain and steel not yielded. Such a design could be deemed over-reinforced considering that steel is not yielded at the ultimate limit state of the cross-section for both positive and negative moments. Should the total steel quantity be reduced to an area equal to 197.9 mm^2, with seven reinforcement bars distributed along the width of the vault, the collapse load would decrease to 38 kN, the concrete and tile vault would reach their ultimate strain for the positive and negative moments, respectively, and steel would yield in both cases. The removal of an extra bar, with a total steel area of 169.6 mm^2, would mean failed steel and the masonry in its plastic range for the negative moment. The ultimate load would then decrease to 33.2 kN. Finally, the parametric study showed a new shift in the cross section's strain domain for the positive moment when reaching a total steel area of 84.8 mm^2, which would correspond to three 6-mm-diameter reinforcement bars. In this case, both for the positive and negative moments, the steel would reach its ultimate

Fig. 24. Formation of the hinge under the load. Composite barrel vault 4.

Fig. 25. Cracks on the extrados of the composite barrel vault 4.

strain and the masonry and the concrete would be in their plastic range.

The following lines present a last example of analysis and design process of the tested barrel vaults 3 and 4 with ELARM, with the aim at a balanced cross-section regarding the materials' strain state, with failure occurring with crushed concrete and masonry and yielded steel, and keeping the loading capacity constant at 53.6 kN (ELARM's predicted ultimate load for the built vaults). This is attained by reducing the amount of reinforcement to a total steel area of 254.5 mm^2, which is equal to nine 6-mm-diameter steel bars, and increasing the concrete layer's thickness to 60 mm. The position of the reinforcement is shifted slightly to remain at the central level of the concrete layer.

7. Conclusions

The construction of the full-scale prototypes demonstrated the feasibility of the proposed building technique for the construction of efficient, economic and expressive composite structures using tile vaults as stay-in-place formwork for reinforced concrete. Furthermore, the load tests on them demonstrated successful struc-

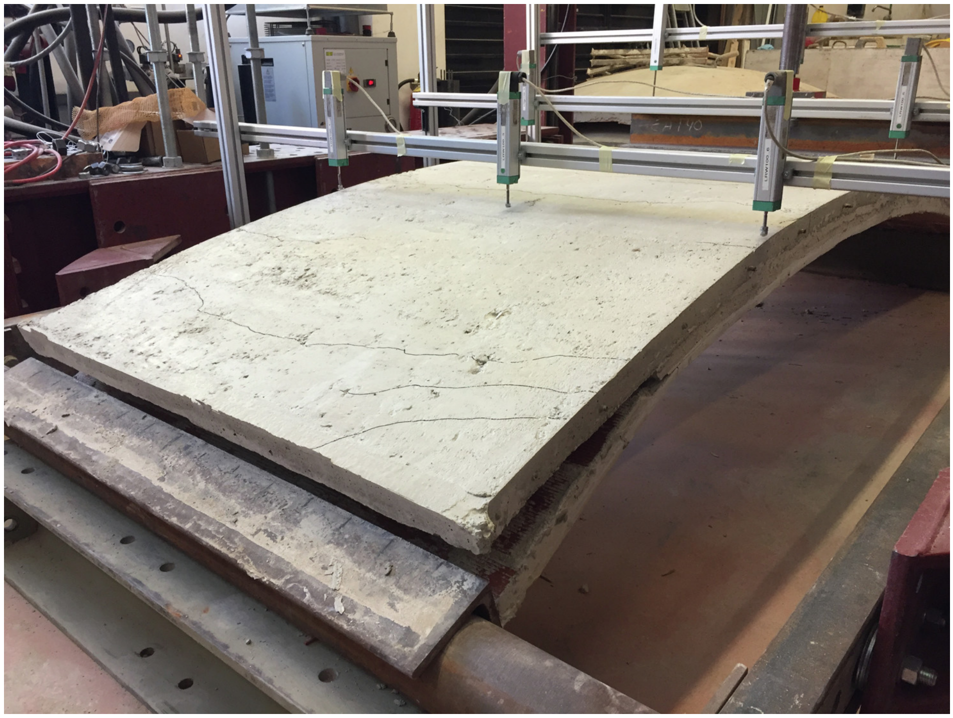

Fig. 26. Debonding between the tile vault and the concrete layer.

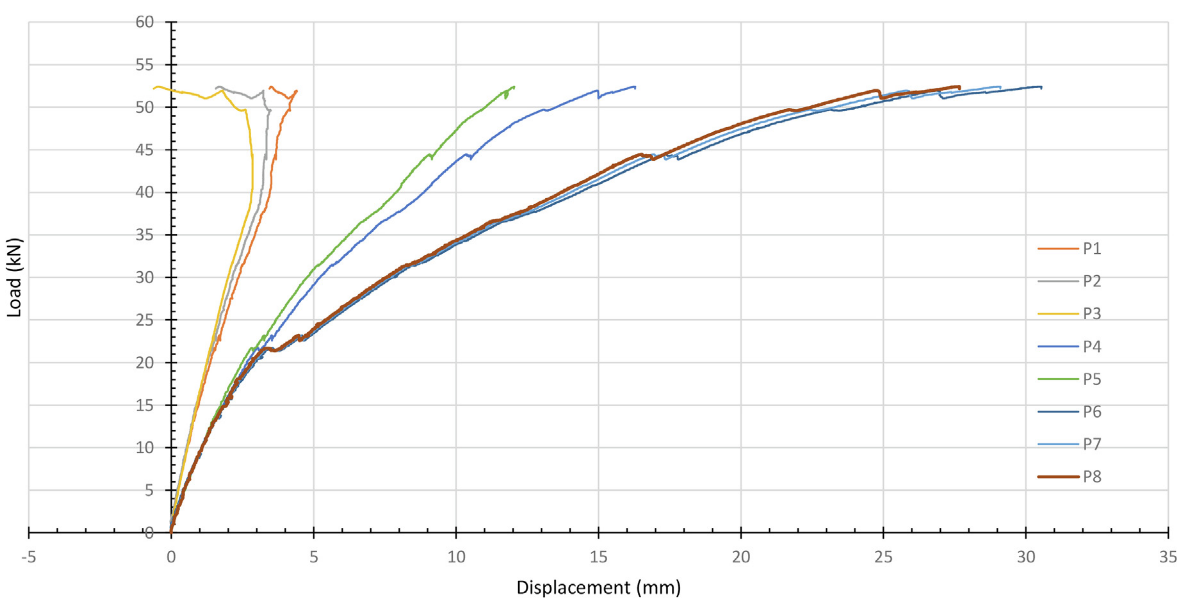

Fig. 27. Load-displacement curves of the composite barrel vault 3.

tural performance with ultimate loads far higher than required by the codes.

The load tests on the composite barrel vaults showed the typical unreinforced masonry arches' collapse mechanism for the described loading setup. However, due to the reinforcement's influence, the hinge at the opposite side from the load, revealed itself at the extrados as a "distributed hinge", associated to several cracks visible on a portion of the concrete surface.

Although debonding of the concrete layer from the tile vault was only reported after the peak load in the steel-reinforced tested specimens, it is worth to mention that the achievement of adequate structural behaviour requires sufficient bond between these layers. As explained in Section 2, a stronger bond could be attained, among others, by designing the concrete mix with proportions of cement and additives according to this purpose, by better controlling the tiles' moisture content at the time of laying and by using

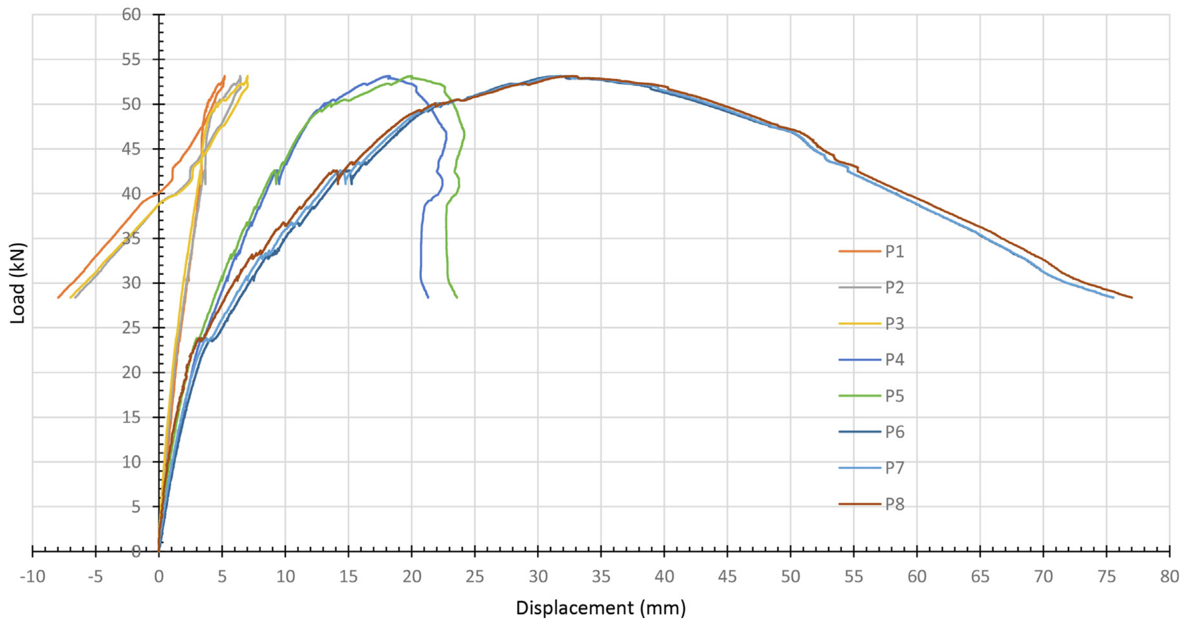

Fig. 28. Load-displacement curves of the composite barrel vault 4.

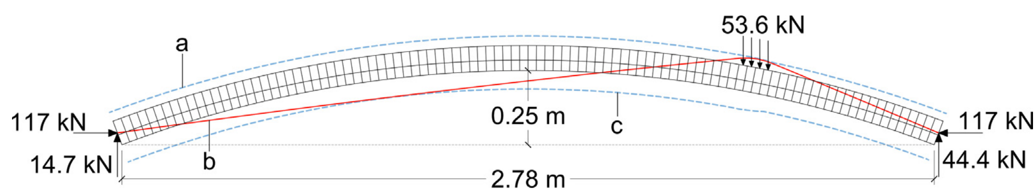

Fig. 29. Application of the uniqueness theorem with ELARM to the tested vaults 3 and 4: a) upper virtual thickness, b) thrust line, and c) lower virtual thickness [1].

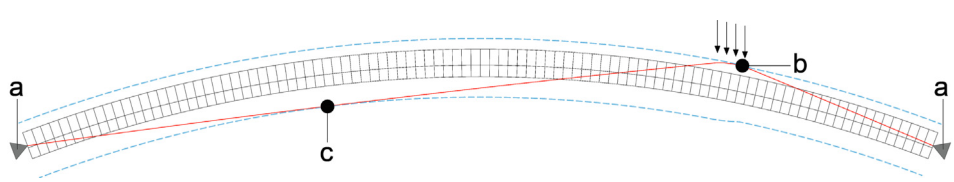

Fig. 30. Application of the uniqueness theorem with ELARM showing the collapse mechanism. a) pinned support, b) first hinge, and c) second hinge.

tiles or bricks with a bigger frog area (having more contact surface with the concrete).

The structural analysis and design method, ELARM, based on limit analysis, is proposed for the assessment of the steel-reinforced composite vaults, which showed a ductile response. The comparison of the experimental tests' results with those provided by ELARM showed the suitability of the method for the structural analysis of the presented construction technique. ELARM allows also a design process to avoid over- or under-reinforced structures in order to attain a response with the desired ductility.

The data registered during the load tests of the prototypes together with the presented experimental research on the materials' properties provide a valuable benchmark for the calibration of eventual further structural models.

8. Future work

The presented construction technique has been experimentally tested with success for composite, singly-curved, barrel vaults. However, the range of structures that can be built using this technique is much wider and includes, among others, doubly-curved, free-form shells, non-funicular structures beyond the masonry's compression-only restriction, long-span structures and shells featuring cantilevers. According to this, an extension of ELARM to fully 3D structures has been developed and will be published soon [39]. Moreover, further experimental research is planned on doubly-curved composite shells, whose results will serve as the basis for the calibration of the Finite Element model that will be defined. As mentioned in Section 4.3, future work will also be aimed at better understanding and quantifying the additional abutments' displacement capacity provided by the concrete layer of the composite system with respect to the plain, unreinforced, tile vault.

CRediT authorship contribution statement

David López López: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Ernest Bernat-Maso:** Data curation, Investigation, Resources, Validation, Writing - review & editing. **Lluís Gil:** Data curation, Investigation, Resources, Validation, Writing - review & editing. **Pere Roca:** Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Swiss National Science Foundation (SNSF, project number P2EZP2_181591).

Second author is a Serra Húnter Fellow.

This research was also sponsored by the construction company URCOTEX, from which Josep Brazo, Antonio Haro and Albert Martí are especially acknowledged. The construction of the prototypes was carried out together with Jordi Domènech, to whom the authors are very thankful as well. Christian Escrig and Luis Mercedes, from the UPC's Laboratory for Technological Innovation in Structures and Materials (LITEM), are acknowledged too for their support during the load tests' setup and during construction respectively.

The authors are likewise thankful to Dr. Diego Aponte and Prof. Marilda Barra (UPC) for their help in the development of the concrete's recipe and their valuable advice in this regard.

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