*IASS Annual Symposium 2019 – Structural Membranes 2019*
Form and Force
7 – 10 October 2019, Barcelona, Spain

# Extended Limit Analysis for Reinforced Masonry applied to steel-reinforced, concrete, tile vaulted structures

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## Abstract

The construction of concrete shells requires formwork with rigid shuttering onto which concrete can be poured and allowed to harden. These formworks are typically complex and unique, and are often not reused. Furthermore, their construction is labour and material intensive, and often even requires a separate foundation. Therefore, formworks for concrete shells are expensive and wasteful. Tile vaults, on the other hand, are unreinforced masonry structures made of thin bricks (tiles) and fast-setting mortar that can be constructed without the need for a formwork, except at the boundaries, making them inherently economic.

Tile vaults can be used as permanent formwork for concrete shells, to reduce construction waste and cost (of the formwork itself but also of the foundation to support the falsework), and thereby provide an interesting solution for the efficient construction of vaulted structures. Concrete would be poured onto a tile-vaulted formwork, afterwards forming a composite structure.

This paper describes a new method to safely design steel-reinforced, concrete, tile-vaulted structures, and assess their strength and stability against external loading. The method is based on Limit Analysis (2D) and Thrust Network Analysis (3D), but takes into account the steel reinforcement by virtually increasing the thickness of the structure accordingly and providing graphical and intuitive results. It is called Extended Limit Analysis for Reinforced Masonry (ELARM) and is also applicable for reinforced concrete, reinforced masonry and reinforced composite (masonry and concrete) shell structures. The new equilibrium method is implemented computationally to fasten iteration processes, provide immediate results and allow for form-finding and optimization procedures.

The feasibility of the proposed construction technique is validated by constructing four full-scale prototypes, namely two composite barrel vaults and two composite sail domes. Furthermore, in order to verify the proposed method, load tests on the prototypes and calibrated FE models are carried out to compare results with those provided by ELARM. Experimental tests on material samples are also performed in order to obtain the values of the material properties to solve the equilibrium equations for the calculation of the new virtual thickness.