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Behavior of thin-walled prestressed concrete roof elements – Experimental investigation and numerical modeling

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ABSTRACT

This paper presents an experimental investigation on thin-walled prestressed concrete roof elements, characterized by different shapes, test arrangements and failure modes (e.g. longitudinal and transverse bending or shear). The aim of this experimental program is to investigate roof elements behavior up to their ultimate capacity under different loading conditions, as well as to study second order effects and the influence of transverse flexure in the optimization of wing reinforcement. The response of tested roof elements is subsequently numerically analyzed, by adopting PARC constitutive model to perform non-linear finite element analyses (NLFEA), able to take into account the interaction between transverse and longitudinal bending, as well as geometric non-linearity. Finally, an application of the proposed numerical procedure for design purposes is also discussed.

1. Introduction

This work deals with the experimental investigation and numerical modeling of the behavior up to failure of thin-walled prestressed concrete roof elements, which are often used for the covering of precast one-story buildings. These elements are placed in parallel lines, by interposing – according to functional reasons – reinforced concrete vaults, sheet-steel panels with an insulating layer or skylights. These elements are designed to cover long spans, which commonly vary from 18 to 30 m. The element width usually equals to 2.5 m, while the maximum adopted element spacing can vary depending on the interposed element weight. In building practice, the used spacing values often range from 3.5 m to 5.5 m. The adopted reinforcement is typically constituted by pre-tensioned strands, placed in the bottom chord and in the top of the wings, and is completed by welded steel meshes, stirrups and longitudinal bars.

The fundamental code that can be used for the design of these thin-walled precast products is the European Standard EN 13693:2009 [1], which defines them as "special roof elements". The special feature of their behavior is represented by the small thickness of the wings, which can lead to local and transverse effects due to the warping of the cross-section and to the deformation of its profile. These latter effects are generally considered in a simplified way in current design practice, by integrating the usual flexural verification in the longitudinal direction (which are carried out following the classical beam theory, according to Eurocode 2 [2]), with local verifications (e.g. related to transverse flexural effects of the loads, shear and torsion effects, etc.). However, according to [1], thin-walled elements behavior should be also verified at ultimate limit state (ULS) by means of both testing and "initial type calculations", made with more precise analytical or numerical models. In more detail, load tests up to failure should be performed before starting a new production on at least two full-scale specimens of any type of product (so called "initial type testing"), in order to check the reliability of the design models assumed for calculations and of the manufacturing processes. The aim of this procedure is to ensure the required resistance and verify possible deviations of the ultimate mechanism from the longitudinal flexural capacity, usually determined on the basis of the sectional bending moment resistance.

Also the scientific research on these special roof elements is primarily based on experimental observations ([3–8]). Such an approach is similar to that followed for other precast floor elements, like hollow core slabs ([9–11]), whose behavior can significantly deviate from beam theory. The collected experimental data are also useful in calibrating finite element models ([12–19]), which can be subsequently adopted for design purposes.

Both experimental tests and numerical studies highlight that mechanical non-linearity can significantly influence the structural behavior of precast roof and floor elements. Moreover, in case of special roof elements, also geometric non-linearity plays a major role, often causing an anticipated failure, not always predictable

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through simplified design procedures. On this point, it can be remembered the approach proposed by di Prisco et al. [3,15], which allows to predict the failure due to transverse flexure by taking into account fictitious distributed loads corresponding to second order effects. Such approach can compute the equilibrium of the transverse cross-section in the middle region of the element, but it is not able to consider any kind of redistribution of these effects because it does not consider the deformation of cross-section.

The experimental investigation presented in this paper involves both longitudinal and transverse flexural tests, as well as shear tests on different typologies of thin-walled roof elements. Aim of this research is to deepen the knowledge of their behavior up to failure, so as to improve both their manufacturing process and their structural performances. Subsequently, the response of tested roof elements is numerically analyzed, by implementing PARC constitutive model [20] into a commercial FE code. The effectiveness of the proposed procedure, which can suitably take into account all the non-linear phenomena influencing the effective behavior of these structural elements, has been verified through detailed comparisons with experimental results. Moreover, the use of the proposed model for design purposes is also discussed, with reference to an example of reinforcement optimization for one of the analyzed roof elements.

2. Experimental research

Different types of thin-walled precast roof elements belongings to Italian productions were experimentally investigated [4,21,22]. In more detail, the research involved:

– Shear tests on two closed-core roof elements, having the same geometry, but different net and shear spans;
– Non-standard flexural tests on two folded plate elements – respectively formed by five and three plates – characterized by different transverse cross-sections, as well as different net spans (almost equal to the maximum value available in the corresponding production);
– Transverse flexural tests on three identical short folded plate elements, formed by three plates.

All the investigated samples were characterized by materials mechanical properties typical of precast production, as summarized in Tables 1 and 2. Table 1 also reports the effective value of concrete compressive strength at the day of the test, as determined on cubes extracted from the same batch of the considered structural element and subjected to the same curing conditions.

The main objectives of this experimental research were: (1) the investigation of thin-walled roof elements behavior up to their ultimate capacity under different loading conditions; (2) the study of second order effects, with reference to long specimens subjected to longitudinal flexure; (3) the influence of transverse flexure in the optimization of wing steel reinforcement.

Table 1
Concrete mechanical properties of all the investigated specimens.

Type of tested element		Concrete	
		$f_{ck,cube}$ (MPa)	$f_{c,cube\ at\ the\ day\ of\ the\ test}$ (MPa)
Closed-core roof elements	Specimen #1	55	67.7
	Specimen #2		63.3
Five plates element		55	80.0
Three plates elements	Long specimen	55	79.7
	Short specimens		80.7

Table 2
Steel mechanical properties of all the investigated specimens.

Reinforcing steel	f_{yk} (MPa) 450	f_{tk} (MPa) 540
Welded mesh	$f_{0,2k}$ (MPa) 390	f_{tk} (MPa) 440
Prestressing steel	$f_{p0,1k}$ (MPa) 1670	f_{pk} (MPa) 1860

This Section focuses on a brief description of the examined specimens and the adopted test setups, while the main experimental outcomes are presented and discussed in Section 3.1, where comparisons with numerical results are also provided.

2.1. Shear tests on closed-core roof elements

Shear tests were carried out in laboratory on two closed-core thin-walled roof elements, having the same geometry and reinforcement, and a slightly different net span (equal to 5.73 m and 5.63 m, respectively for specimen #1 and #2, [4]). The investigated elements, whose geometry is depicted in Fig. 1a, were characterized by two 45 degrees inclined wings, with thickness ranging from 47 to 85 mm. At element heads the closed core was missing, and the transverse cross-section became open and 0.74 m high (Fig. 1b).

The experimental test setup is shown in Fig. 2. Vertical loads were applied by means of two hydraulic jacks placed symmetrically with respect to the transverse cross-section (Fig. 2a) so as to avoid torsional effects. Two slightly different shear spans were considered, according to Fig. 2b.

Three linear variable differential transformers (LVDTs) were employed to measure vertical displacements under the loading point (v_c), as well as in correspondence of supports (v_s and v_d). Moreover, further 18 LVDTs were placed in proximity of the support nearest to the applied load (Fig. 3a and b), so as to monitor the behavior of element dapped ends. All the instruments were removed before the reaching of the ultimate load, for safety reasons.

The two investigated specimens were characterized by a similar crack pattern development, due to the transfer of compressive internal forces from roof element wings to the support. Owing to the low values of shear span to depth ratio (l_1/d), the behavior was indeed governed by an arch mechanism, so leading to a shear-compression failure. Specimen #1 failed for concrete crushing near support, as highlighted in Fig. 3c, while specimen #2 failed due to cut-off in correspondence with rebar superposition, where the concrete resistant section was reduced.

2.2. Longitudinal flexural test on a five plates roof element

A non-standard longitudinal flexural test was performed on a full-scale open-core five plates roof element at the production plant of its Manufacturer Company [21]. The considered element, whose geometry is depicted in Fig. 4, was characterized by two wings of variable thickness, ranging from about 55 to 180 mm. The inclination of the wings was almost sub-vertical in their bottom part, while it assumed a 30 degrees inclination at about mid-height of the transverse cross-section. The tested specimen was 27.5 m long and was reinforced with ordinary steel bars and welded-wire meshes (Fig. 4a, referred to the current cross-section, 1.3 m far from element heads), as well as with 20 strands having a diameter of 0.6 inches (Fig. 4b).