Structural design of a precast frame for the housing of silos

Beatrice BELLETTI
Researcher
University of Parma
Parma, Italy

Patrizia BERNARDI
Assistant Researcher
University of Parma
Parma, Italy

Gianluca TODESCHINI
Structural Engineer
R.D.B. Group
Piacenza, Italy

Nello VISCONTI
Structural Engineer
R.D.B. Group
Piacenza, Italy

Summary

In this paper, the realization of a terminal for the storage of plastic materials, carried out by RDB for the Katoen Natie Group, will be presented. The structural complex is characterized by a special reinforced concrete frame, constituted by curved precast concrete beams which must allow for the housing of aluminium silos where the plastic materials are collected. The realization and the assembling of the frame, which requires very low tolerances with respect to usual reinforced concrete structures, will be carefully described. The curved beams have been designed by following Eurocode 2 prescriptions, and their structural response has been verified by performing non-linear finite element analyses, in which the non-linear mechanical behaviour is considered by implementing the PARC constitutive model into a FE Code. Comparisons between the theoretical (EC2) and numerical (NLFEA) responses at SLS and ULS will be provided.

Keywords: precast, reinforced concrete, frame, assembly, silos, load combinations, serviceability, nonlinear finite element analysis, shell elements.

1. Introduction

This work focuses on the realization of a structural building, designed by R.D.B. for the Katoen Natie Group, which is intended for a large warehouse of plastic materials. In order to contain the semi-manufactured product, three lines of 14 aluminium silos, 5.6 m in diameter, and 20 m high, have been planned (Fig. 1). The whole building is composed by two main bodies, one of them occupied by offices and storehouses (for 12731 m^2), and the second one by the silos (for 1651 m^2). The static independence between these two areas has been achieved by means of a structural joint, which has been obtained by dividing the common pillars. The most distinctive features of the building concern the structural details of the area where the silos have to be placed. Here, a 6x6 m reinforced concrete frame has been built, characterized by an intermediate, 5.2 m high floor system and a grid of beams, whose supports are 14.2 m high and which have been designed to support the silos.

Fig.1 View of the area of the terminal occupied by the silos.

During the design and the execution of the structural project, several difficulties had to be overtaken. The most critical points concerned first of all the high loads induced by the silos to the frame, secondly the high precision required to join the metal to the concrete structures, and lastly the execution of the connections. Moreover, the intermediate floor, on which an actuator has to move for the collection of the material, had to be made without joints in all its length, which was about 84.90 m.

The most characterising structural element of the frame has been identified with the beam which has been expressly designed to house the silos' curved surface. For this reason, in the following this element will be described more in details, and it will be verified and analysed not only by means of the code prescriptions (according to Eurocode 2), but also through a non-linear finite element procedure able to account for the most important features of the serviceability and ultimate limit states.

2. Structural design of the building

2.1. Design of the curved beam supporting the silos

The design of the beams supporting the silos has been influenced by the geometrical constraint represented by the circular profile of the silos. It has been decided to adopt a T-section with a variable width wing (ranging from 2.25 m to 0.72 m), in order to follow the silos shape and to provide a continuous support, also avoiding stress concentration. The geometrical details and the reinforcement arrangement of the curved beams is reported in Figure 2.

The web width is dependent on the minimum dimension of the beam wing and has been set equal to 0.72 m. The height of the wing is equal to 0.50 m, with an offset 0.03 m high and 0.28 m wide for the housing of the silos ring. The web height is equal to 1 or 1.2 m, according to whether the beam supports a silo of 3050 kN or 5080 kN capacity, respectively. The correspondent beam's dead loads are variable between 180 kN and 220 kN, respectively.

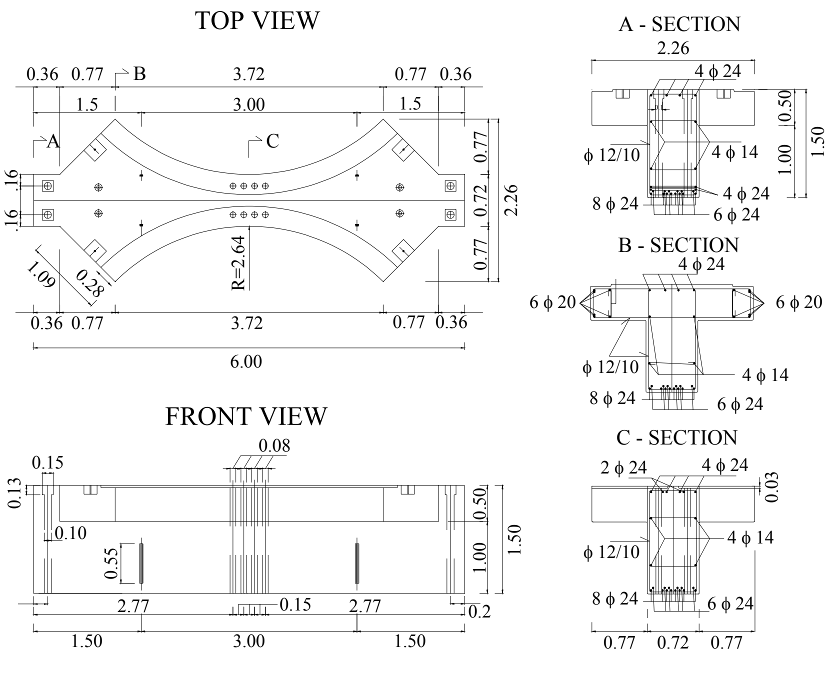


Fig. 2 Geometrical details (dimensions in m) and reinforcement arrangement for the curved beams.

In the reinforcement design, particular attention has been taken to the presence of shear and torsional stresses, not only because of the short span and the type of loading, but also because of the beam's geometry, which shows a behavior similar to a deep beam. In order to provide an anchorage to the silos, at beam's midspan, in correspondence of each side, four vertical 8 cm diameter holes have been placed. In the holes, high strength threaded bars, 2.4 cm in diameter have been inserted and fixed in the beam's bottom side by means of metal plates and double nuts. In a second time, the holes have been filled through a concrete casting, which provides both a protection and a static help through the tangential slip stresses. The same method has been used also to fix the beams to the pillars, but for the holes (two for each beam's end) a diameter equal to 10 cm has been adopted.

Rotations around longitudinal axis of the beams and differential displacements between them have been limited by using 1 cm thick metal plates, placed nearby the maximum wing opening (Fig. 2).

2.2. Precast elements assemblage

The assemblage between the beams and the silos has been carried out by placing in the bottom side of the silos a metal ring with holes (to screw the bars) in correspondence of those of the beam (Fig. 3a, 3b). Because of the different level of tolerance in the manufacturing and assemblage of concrete and metal structure, during the manufacturing of the beams, a metal template, which has been provided by the silos producers, has been used, so to guarantee the coincidence between the holes of the silos ring and those of the beam.

Fig.3 (a) Precast curved beams assemblage; (b) connection between the frame and the silos.

The horizontal forces, which are due to the wind action, and to the silos conventional horizontal force, are supported partly by the pillars, which have a square, 0.90 m side, cross-section, and by metal cross bracings constituted by HEA beams (Fig. 4). In the intermediate floor system, the moving of an actuator for the opening and the closing of the hopper of the silos has to be allowed; as this machine requires a perfectly smooth surface, the floor has been made with special resins and without joints (Fig. 4). The actuator's movement produces a variable load equal to 17.00 kN/m^2. To reduce the horizontal displacements and the instability of the pillars, at the intermediate floor the reinforcement in the frame corners has been detailed so to provide semi-fixed joints. In order to increase the global stiffness of the structure, slugs of reinforcement at right angle with respect to the beams have been placed, so to guarantee the continuity of the floor and a monolithic behavior. These bars have been located within a 12 cm thick fiber-reinforced concrete structural slab.

Fig. 4 Final frame ready for the housing of the silos.

Since the complex lies near the Po river, the ground consists of high power sand deposits, which are quite susceptible to groundwater variation; for this reason, a deep foundation system constituted by bearing piles has been chosen. In the area which is occupied by stores and offices, at the top of the piles (four for each pillar) a 0.80 m thick foundation plate has been placed, and above it the precast collar for the housing of the pillars has been placed. In the area occupied by the silos, a net of grade beams, with a variable height between 1 and 1.5 m and a mesh equal to that of the overhanging structure has been adopted. In correspondence of the silos with the highest capacity, a ribbed mat has been preferred.

3. Linear elastic analysis of the curved beams

3.1. Combinations of actions according to Eurocode 2 prescriptions

The curved beams have been designed so to satisfy the verifications at serviceability and ultimate limit states as prescribed by Eurocode 2. Each beam has been hypothesised as simply supported, with a design span l = 5.6 m, and all the design permanent and variable actions have been opportunely considered. More in details, three fundamental actions have been identified: the beam's dead load, the load induced by the silos to the beams and the wind action. With regard to the computation of the load transmitted by the silos, it has been considered that a single beam can house at the most two silos, each of them inducing a minimum load, $Q_{s,min}$=157 kN, (in the case of empty silos), and a maximum load $Q_{s,max}$= 3150 kN (which includes the empty silos dead weight as well as the plastic material's weight). This load has been spread on the 0.28 wide ring where the silos leans on the beam. The moment at midspan and the shear force at supports (Tab. 1) have been determined for the case of two full silos acting on the same beam, while the limit case represented by one full and one empty silo on the same beam has been considered by means of the correspondent torsional moment T at supports. The wind action is represented by the resulting horizontal force and the correspondent moment at the beam level, which are then transposed into equivalent concentrated vertical forces acting on the connections placed at the beam's midspan (see Fig. 2). The obtained values of the bending moment at midspan, of the shear force and the torsional moment at supports for each type of loading condition are reported in Table 1. The correspondent ultimate and serviceability limit state design values are reported in Table 2 and 3, respectively.

Table 1 Forces correspondent to each different type of loading acting on the beam.

	Dead load	Silos Load	Wind action
V_{max} at supports (kN)	99.7	401.1	84.85
M_{max} at midspan (kNm)	125.95	2*728.2	237.60
T_{max} at supports (kNm)	-	249.90	-

Table 2 Ultimate limit state verifications

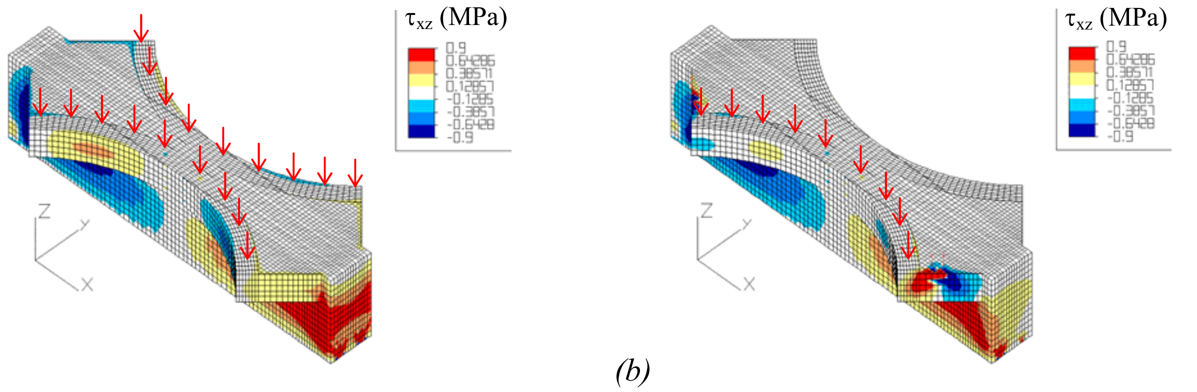
Bending		Shear		Torsion		Shear+Torsion	
M_{Ed} (kNm)	M_{Rd} (kNm)	V_{Ed} (kN)	$V_{Rd, min}$ (kN)	T_{Ed}(KNm)	$T_{Rd,min}$ (kNm)	combination	Limit value
2717.35	3274.20	1470.15	1779.54	374.85	429.95	0.46	1

Table 3 Serviceability limit state combinations

$M_{Ed, characteristic}$ (kNm)	$M_{Ed, frequent}$ (kNm)	$M_{Ed, quasi-permanent}$ (kNm)	$M_{cracking}$ (kNm)
1748.70	1484.25	1145.45	1557.65

3.2. Finite element linear elastic analysis

Since it was not possible to carry out experimental tests up to rupture, the simplest tool to improve the understanding of the structural behavior of the curved beams has been to perform finite element analyses able to simulate the effective loading conditions which the beams must afford when inserted in the final frame. First of all, a linear-elastic finite element analysis has been performed through the Supersap Code, by subdividing the beam into a mesh of brick elements (Fig. 5). In this way, the beam's effective geometry could be accurately reproduced. The beam has been constrained by hinges, simulating the effect of the pins connecting the beam to the understanding pillar, and by vertical springs, placed in the beam's wings, reproducing the constraint represented by the presence of the contiguous beams. The three serviceability limit states combinations (Tab. 3) have been considered, not only for the case of the concurrent action of two full silos but also for the case of one empty silo. The resulting numerical stress field in terms of tangential stresses for these two different loading conditions are represented in Figures 5a and 5b, respectively, for the frequent combination of actions

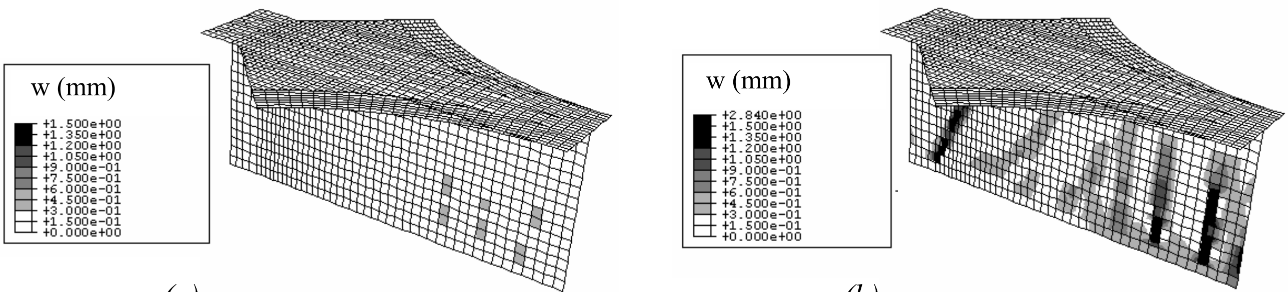


(a) *(b)*

Fig. 5 Tangential stresses at support sections for the frequent combination of actions in the case of (a) two concurrent full silos (b) one full and one empty silo acting on the beam.

4. Non-linear finite element analysis

In order to obtain a complete description up to failure of the beam's structural response, non-linear finite element analyses able to account for the non-linear mechanical behavior of the reinforced concrete element have been carried out. The analyses have been performed by simulating the mechanical behavior through the PARC constitutive model [1], which is a smeared, fixed crack model determined for membrane elements subjected to in-plane stresses. This model is represented by a secant stiffness matrix, which assumes different forms depending whether the membrane element is uncracked or cracked (the complete formulation can be found in details in [2] and [1], respectively). In the cracked stage, the strain components are determined as functions of the crack opening, the crack slip and the strain of the concrete strut, and the stiffness matrix takes into account the contributions of the main phenomena occurring after cracking. The constitutive matrix is then implemented into a FE Code (ABAQUS), which allows the user to insert the chosen constitutive behavior of the material. This procedure has already been applied to the analysis of several reinforced concrete structures, such as beams, [4], precast roof elements, [3], hollow core slabs [5], providing in each case good correlations with the experimental observations. The reinforced concrete curved beam has been subdivided into a mesh of multi-layered shell elements, which are three-dimensional finite elements constituted by several layers (three, in the performed analyses). Each layer can then be considered subjected to in-plane stresses, and the PARC model can be adopted to adequately describe the constitutive shell response. According to the fundamental hypotheses of the PARC model, the reinforcement, which can be present in one ore more layers, has been introduced by smearing its effect between the bar spacing. The resulting mesh of shell elements is represented in Figure 6. As can be observed, for non-linear analyses only half of the beam has been modeled, taking advantage of the structural symmetry.



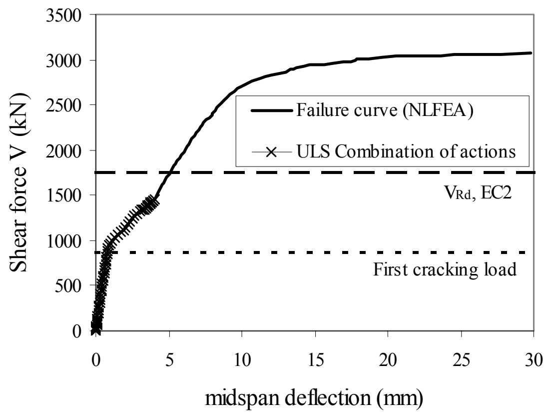
(a) *(b)*

Fig. 6 Cracking pattern (a) at first cracking; (b) at failure.

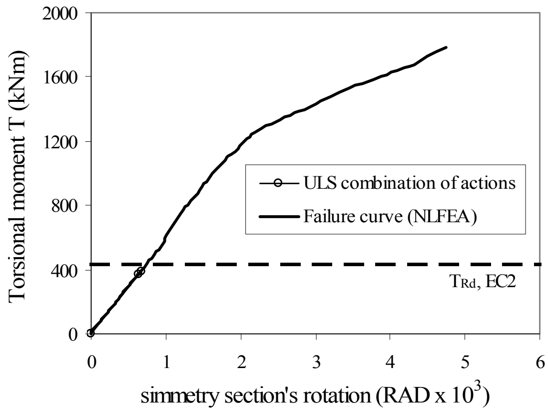
Through the performed analyses, several information have been obtained. First of all, the combinations of actions at serviceability have been simulated. Through the adopted model, it has been possible to valuate the crack opening w and the stresses in the concrete and in the reinforcement and compare them with the values of EC2 simplified methods (Table 4). Secondly, a nonlinear analysis up to failure has been performed: the cracking patterns at different loading stages have been provided (Fig.6) and the numerical ultimate load has been determined and compared to the correspondent resistant value obtainable on the basis of EC2 prescription.

Table 4 Comparisons between theoretical (EC2) and numerical (NLFEA) SLS quantities

Eurocode 2 (quasi-permanent combination)			NLFEA		
w_k (mm)	σ_c (MPa)	σ_s (MPa)	$w_{k,\,max}$ (mm)	σ_c (MPa)	σ_s (MPa)
0.20	18.60	308.0	0.012	5.33	42.3



(a)



(b)

Fig. 7 Numerical failure curves superposed on the limit values prescribed by Eurocode 2 in terms of (a) reaction force at support-midspan deflection for two concurrent silos, (b)torsional moment-rotation in the midspan section due to non symmetrical loading (only one full silo).

5. Conclusions

In this work, the structural design of a particular reinforced concrete frame constituted by curved beams has been presented. The design procedure followed two parallel ways: first of all, the required prescriptions according to EC2 were verified, both at serviceability and ultimate limit state, and after that, non-linear finite element analyses were performed, which allowed for a verification of the most important variables affecting the behavior at serviceability limit state (crack width, stresses in concrete and steel) and an improved understanding of the structural response of the element in correspondence of the failure. This design example show the application of non-linear finite element analysis as an useful tool to complete the information about particular shaped structures, which cannot be experimentally investigated, and which show a peculiar structural response that can not be completely covered by the code prescriptions.

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