SECM/15/178

Structural Feasibility of a Pre-Cast Building System

P.L.N. Fernando [1*] and C. Jayasinghe [2]

[1]Research Assistant, University of Moratuwa, Moratuwa, Sri Lanka
[2] Professor, University of Moratuwa, Moratuwa, Sri Lanka
*E-Mail: lakshitha_f@yahoo.com, TP: +94779744941

Abstract: This paper is based on a case study on a model house, which is to be built with slabs, beams and columns, constructed using pre stressed concrete and wall panels constructed out of Expanded Polystyrene. The proposed system is a solution to the fast growing issue of increased demand for housing and buildings and will contribute towards sustainable development with its cost effectiveness and optimized usage of resources. The beams, slabs and columns are pre-stressed in the form of pre-tensioning and Dowell bars are used at the beam-column junctions. As for the wall panels, a mix design would be carried out to identify the optimum cement, fly ash, sand, Expanded Polystyrene proportions. Seismic design has become an integral component in modern day engineering and hence, its implications on a pre-stressed concrete structure and a method to evaluate the feasibility of the proposed system in terms of its ability to withstand the effect due to earthquakes are proposed in the paper.

Keywords: Connections, Expanded Polystyrene, Pre-stressed Concrete, Seismic Design

1. Introduction

Increased demand for housing and buildings has led designers to seek for alternative construction techniques. This is due to the requirement of massive amounts of building material and labour for conventional construction methods, which in fact have already crossed the boundaries of sustainability. In this context, Pre-cast building systems can exhibit a lot of promise with optimized use of material and labour, which in turn would reduce the use of natural resources.

Additionally, given the growing concerns regarding disaster resisting structures due to the recent history of earthquakes in the South East Asia region, these new building systems should be checked for its ability to withstand such disasters.

This research paper is based on a case study carried out for one such initiative, where a model house is to be built with slabs, beams and columns, constructed using pre stressed concrete and wall panels constructed out of Expanded polystyrene. The proposed system will contribute towards sustainable development with its cost effectiveness and optimized usage of resources.

2. Pre-stressed concrete as a pre-cast material

Usage of Pre- stressed concrete as a construction material has been on the rise in Sri Lanka. In fact, increased use of pre-stressed concrete has provided a boom to the pre-cast concrete industry. Simplification of the construction processes (especially at construction sites), along with the obvious savings in terms of time and money and relative ease in quality assurance has led to its widespread use in Sri Lanka.

As far as pre-stressed concrete is concerned, there are two ways of applying the required pre-stress to the concrete, i.e. pre-tensioning and post-tensioning. In both cases, steel wires, strands or cables are used to transfer the pre-stress force to the concrete. This case study focuses on a pre-tensioned system.

At this particular yard, the option of pre-tensioning was chosen due to ease of construction. Generally, post- tensioning would require placing of ducts, which should be carried out accurately. Furthermore, it would also require grouting to provide sufficient bonding between the pre-stressing tendons and concrete. Additionally, unlike in pre-tensioning, special anchoring mechanisms as well as additional helical reinforcement is required at the end regions to counter the transverse tensile stress induced due to large concentrated forces during the jacking process. However, since pre-tensioning is carried out prior to concreting, the aforementioned issues would not occur. Additionally, since the design loading for a house is expected to be relatively low and uniform, a straight tendon profile, as opposed to a curved profile could be maintained. Hence, once all these factors are taken into account, pre-tensioning seems the more convenient, cost effective and feasible option.

3. Pre-Cast Elements

3.1 Beams

Generally, the beams were cast as 150mm x 350mm and the maximum span of a beam was 5 m. The pre-tension force was applied through 8 numbers of 5 mm diameter tendons. In addition, two numbers of T12 bars were used as nominal bottom reinforcement and R6 shear links were placed at 250 mm intervals. The covering to shear links was maintained at 20mm. Grade 40 concrete was used to cast the beams at the yard. A cross section of the beam is illustrated in figure 1 below.

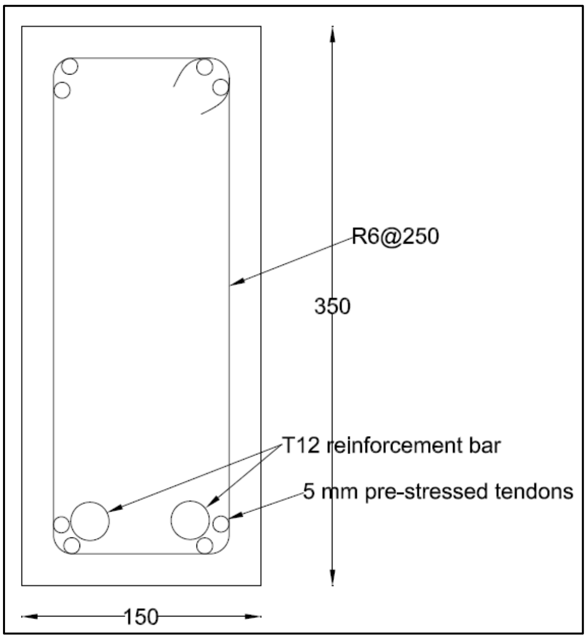

Figure 1: Cross section of a typical beam (all dimensions in mm)

3.2 Slabs

The slabs were produced in two sizes, 6m x 1m and 4m x 1m. However, both these types had a thickness of 75mm. Furthermore, a 45mm thick screed was laid after placing a net of reinforcement of 6mm diameter in the form of a 200mm x 200mm grid (see figure 2). As far as pre-stressing tendons are concerned, the larger slab panels were provided with 16 numbers of pre-stressing tendons, while corresponding number for the smaller panels was 14.

In both the beams and slabs, pre tension force of 2 tons (= 20 kN), were applied to each tendon. The elongation of the steel tendons were monitored and measured to ensure the expected pre- tension force was actually applied.

Figure 2: Reinforcement net on a pre-stressed concrete slab panel before prior to screed concreting

3.3 Columns

The columns were sized as 200mm x 200mm, so as to ensure a bearing of 50mm at each end at beam-column junctions and the columns contained 8 numbers of 5mm diameter pre-stressing tendons.

3.4 Beam-Column Joints

Generally, joints in pre-stressed concrete structures are designed as simply supported, as opposed to the usual practice of fixed joints in reinforced concrete. This would thus eliminate the hogging moments at the joints and therefore render the top reinforcement of beams uncritical. However, this would increase the sagging moments at mid span of beams and hence would require additional pre-stressing to ensure the additional sagging moment is countered through the hogging moment caused due to pre-stressing.

A SAP2000 analysis of a framed structure with 9 bays, each having dimensions of 6m on all sides (see figure 3) was carried out to illustrate the impact of joint conditions on the design moments of a beam. The elements were assigned the properties of concrete and the imposed load was considered as $2kN/m^2$. The analysis was carried out for serviceability limit state.

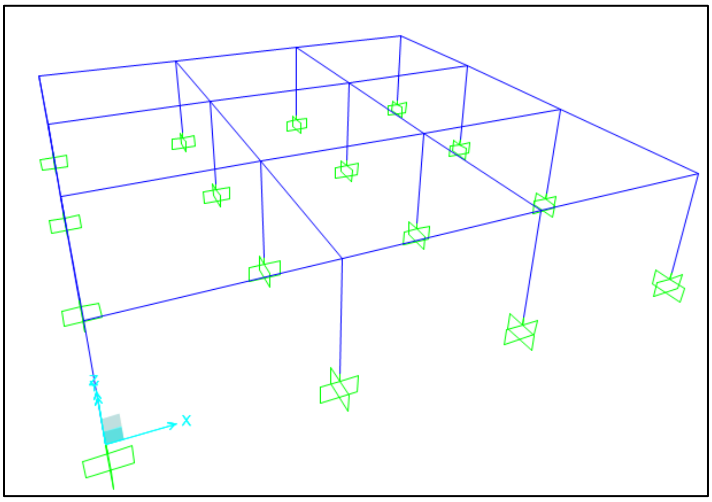

Figure 3: SAP2000 view of the modeled frame

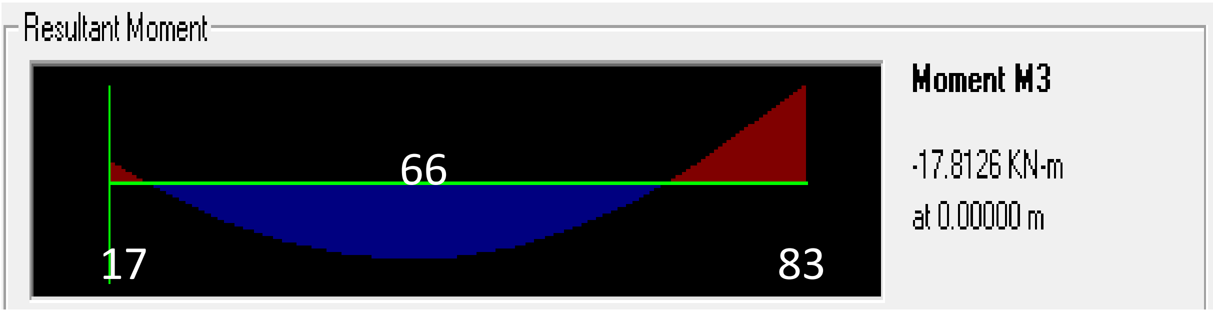

Figure 4: Variation of bending moment for a critical beam under fixed joint connections

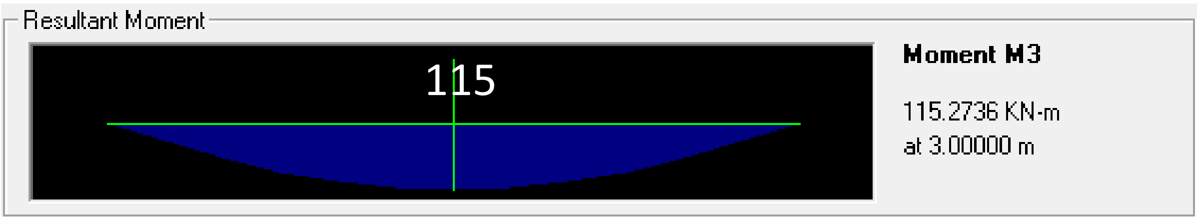

Figure 5: Variation of bending moment for a critical beam under simply supported joint connection

Figure 4 illustrates the variation of bending moment for the beam experiencing the highest hogging moment (83 kNm) and sagging moment (66 kNm) under fixed joint conditions. The variation of bending moments for the same beam, which in fact experiences the greatest sagging moment (115 kNm) under simply supported joint conditions, is illustrated in figure 5.

Although the eventual sagging moment has almost doubled, since providing the required sagging moment capacity is much easier and less expensive due to the effects of pre-stressing, elimination of the relatively high hogging moment is beneficial.

However, achieving continuity at joints is critical during construction. But, constructing connections that achieve continuity at supports is usually complex. In order to achieve connectivity, two numbers of Dowell bars of 20mm diameter were anchored 40mm into the columns using chemical anchoring, to ensure adequate strength at connection joints (see figure 6).

Figure 6: A typical beam-column joint

3.5 Wall panels

The proposed wall panel is to be constructed in the form of Light Weight Compound Sandwich Wall Panel. It consists of two fiber cement boards or calcium silicate boards which act as a reinforcement to the in-filled foam concrete (see figure 7).

Figure 7: View of a wall panel

Foam concrete is a type of lightweight concrete and hence, has the advantages of possessing a high flowability and minimal consumption of aggregate. Additionally, foam concrete has low densities typically ranging from 400 – 1600 kg/m^3 [1]. The foam concrete which is to be used for the proposed wall panel will consist of cement, sand expanded polystyrene and fly ash. It is expected that a certain proportion of cement and sand could be replaced by fly ash and expanded polystyrene respectively (to ensure gaining of adequate strength, albeit at a lower density).

However, the use of foam concrete in structural applications is quite limited due to its low compressive strength [1]. But on the other hand, since these wall panels would not be load bearing walls (since the house is expected to act as a framed structure), a compressive strength sufficient to carry its self-weight would provide a feasible wall panel. Furthermore, the wall panels should be able to withstand the lateral forces, especially due to wind loads and hence, the flexural capacity of the panels would also be critical.

Taking into account the above facts, a mix design would be carried out to identify the optimum mix for the Light Weight Compound Sandwich Wall Panel. The main objectives of the design are to determine the optimum fly ash content to ensure highest compressive and flexural strengths and to determine the optimum replacement percentage of Expanded Polystyrene with Recycled Polystyrene for the identified fly ash content.

Previous research suggests a ratio of 1:1:2 for cement to sand to expanded polystyrene with a water cement ratio of 0.4. However, this is for a density of 1250 kg/m^3 [1]. Meanwhile, for another research with a water cement ratio of 0.65, it was found that the compressive strength had increased with the increasing addition of fly ash. However the flexural strength decreased with the increasing addition of fly ash up to a 9% by weight [2].

As for the proposed test method for the first objective, the fly ash content would be increased from 0 % to 30 % in increments of 5% and for each case, sand will be replaced with polystyrene by 10%, 20% and 30%. The target density of the wall panel is 600kg/m^3.

The testing of compressive strength will be carried out by casting and testing cubes according to BS EN 12390-2: 2009 [3] and the flexural strength will be determined for prismatic moulds using ASTM C348 [4]

As far as the construction of wall panels is concerned, it would be fully automated and hence would reduce the workmanship defects of a typical wall construction.

4. Study on Performance under Earthquake

Seismic design has become an integral component in modern day engineering and hence the feasibility of the proposed system in terms of its ability to withstand the effect due to an earthquake needs to be studied.

Pre stressed concrete elements are expected to remain uncracked for longer periods compared to reinforced concrete elements in the event of cyclic loadings such as earthquakes and hence would contribute more towards an important area of disaster resistant buildings. However, the structural discontinuity, especially at joints, is an area of concern and hence designing and detailing of such joints requires special attention

As far as seismic design is concerned, the restoring force and the energy dissipation capability of a structure are considered critical factors [5]. Hence, these aspects of a pre-stressed concrete structure should be studied and compared and contrasted with other construction technics, in order to identify its feasibility in seismic design.

4.1 Comparison between Reinforced concrete structures and pre-stressed concrete structures

Extensive research, both analytical and experimental has been carried out for reinforced concrete structures and many design and detailing technics are being incorporated into structures. One main drawback in reinforced concrete structures is that although it is possible to enhance the ultimate strength of buildings through increasing the reinforcement ratio and thereby the ability to dissipate energy under cyclic loading, the serviceability, i.e. crack widths of beams and slabs under gravity loading, cannot be improved [6].

On the other hand, a drawback in pre-stressed concrete structures is that, although it enables designers to use longer spans, this could cause the structures to be more flexible and hence the natural period of vibration would be lower. Therefore, this would lead to a smaller design seismic load [6].

However, using of pre-stressed concrete would enable the designers to use higher grades of concrete and hence this would enhance the compressive strength and the elastic modulus of the elements [6].

Previous research has indicated that displacements and inter-storey drifts are generally similar for reinforced concrete and pre-stressed concrete structures. However, it must be noted that the dynamic response of a structure would largely depend on the structural configuration and the ground acceleration [6].

Compared to reinforced concrete frames, pre-stressed concrete frames would exhibit larger ground motions. This could be attributed to the fact that the pre-stressed concrete members usually have higher moments at the commencement of flexural cracking than the reinforced concrete members, and they recover to their original states and respond elastically even after they are loaded up to near their ultimate strengths [6].

In addition, the performance of the beam-column joints can have a large influence on the response of the frame to ground motions, although joint cores are usually assumed to have high rigidity [6]. However, this could be a critical aspect, due to the state of the connections for pre-stressed concrete structures.

As far as seismic design is concerned, the effect of pre-stressing could be advantageous. Prestress introduced into a beam has been shown to improve the shear resistance of beam-column joints. The reason is the biaxial compression in the joint core due to the joint core’s compression in the horizontal direction as well as in the vertical direction due to the axial force on the column. Also, prestressing is considered to increase the diagonal compression strut action in the joint core because the prestress results in a larger neutral axis depth. In addition, prestress can help preserve the rigidity of the joint cores. Stiffness degradation in joints can result in pinched hysteresis loops with reduced energy dissipation [6].

4.2 Analysis Procedure

The behaviour of the proposed system under seismic loads will be analysed using Finite Element Modelling.

The required structural properties of the elements will be tested experimentally. Standard flexural test of ASTM C78 using simple beam with third-point loading will be carried out for the beams and slabs

[7]. Standard Test Methods of Conducting Strength Tests of Panels for Building Construction mentioned in ASTM E72 will be followed to determine the flexural and compressive strengths of the wall panel [8].

The model house will be modelled in SAP2000 incorporating the relevant structural properties and will be analysed for a suitable response spectrum in order to identify the critical results such as base shear, acceleration, deflections and storey drifts.

5. Conclusions

The paper presents a proposed pre-cast building system for a house, with details related to the structural aspects of individual elements of the house. The possibility of replacing a certain proportion of cement by fly ash and sand by Expanded Polystyrene and Recycled Polystyrene is explored by testing samples for compressive and flexural strengths, while targeting a density of 600 kg/m^3.

A finite element analysis of the model house is proposed to determine its behaviour in the event of an earthquake.

Acknowledgement

The authors wish to acknowledge the assistance given by Mr. Neranjan Fernando.

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