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Numerical Modelling for System-Level Structural Performance of 3D Printed Concrete Structures

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Abstract - 3D printing of concrete is a promising technical revolution of the construction industry aimed at bringing in the ease of construction, sustainability alongside the architectural intricacies. Given the novelty of 3D printing, the R&D focus has primarily been on aspects such as plastic state properties of concrete, printability and automation, with structural system-level performance and structural design basis of 3D printed structural components yet to receive the necessary focus. This study deals with the post construction analysis of 3DPC structures to examine their static and dynamic behavior at structural system-level. Dynamic Identification (DI) of a functional structure (3D- Printed) was carried non-destructively through ambient vibration testing (AVT) to quantify its dynamic behaviour, develop a calibrated numerical model, and study its response to gravity and lateral loads. Subsequently, this study developed a finite element based numerical model that could be used to perform structural analysis to develop design guidelines for structures built using this technology.

***Keywords*:** 3D printed concrete, ambient vibration, mode shapes, dynamic identification.

1. Introduction

The civil engineering industry along with its infrastructure is the main consumer of energy and emitter of greenhouse gases especially CO_2 during cement production and other processes. To limit its influence in deteriorating the environment and addressing the rapidly negatively changing climate the humanity is experiencing, multiple pronged approach is needed from civil engineers. One is the material aspect of civil engineering products which need to be produced in concurrence with the environment friendly approaches and the other less thought about, yet classical and promising approach is the need for creating structurally and materially efficient structures. It is where the role of structural engineers comes grossly into the picture to contribute in producing structurally optimized structures or structural components. 3DPC is one such modern day technology still in its nascent stage that is promising in its approach of creating efficient structures through optimised use of materials.

3DPC structures are evolving from prototypes to full-scale applications in the construction sector [1]. However, 3DPC still lacks compliance with structural integrity requirements, which hinders its applicability on a structural level[2]. Not all 3D Printed structures are put into use for a simple cause of them not qualifying the safety requirements[3].On material level, concrete acting like the 'ink" of 3D printer warrants a specific workability and material mix proportion for printing. But on a structural level, it requires to fulfill the necessary strength parameters including adhesion, rigidity to print high-rise structures[3]. Furthermore, on the durability part, conventionally produced concrete is typically viewed as isotropic with regards to its hardened properties, such as density, porosity, and durability. However, in 3D concrete printing, the layer-by-layer method can lead to an uneven distribution of these properties[4]. Many authors have indicated that 3D printed components present lower strengths compared to conventionally cast components[1], [5]. However, all of such studies are limited to material or component levels and there is an imminent need to investigate the structural performance of large-scale structures built using 3D concrete printing technology. Therefore, this study examined an already built, functional 3DPC structure (bus shelter) in India for analyzing behavior under gravity and lateral loads. The numerical model of the structure was also validated against ambient vibration experiment carried out on the structure.

Experimentally, non-destructive ambient vibration testing (AVT) has been used as a precise method for identifying dynamic properties of structural systems [6].The dynamic parameters such as eigen frequencies, eigenvalues, eigenvectors, and damping ratios etc contribute to the global response of any structure. Identifying and subsequently quantifying such dynamic features of a structure is essential and a subject of immense engineering significance.

The primary objective of this study is to determine the features of the structure as a system under the actual conditions to which they will be subjected to during their service life. In the present study, the ambient vibration test has been carried out on a 3DPC bus shelter to obtain the necessary dynamic parameters of these 3DPC structures. The experimental eigen frequencies corresponding to each mode shape showed a strong correlation with the parameters obtained from the numerical (FEM) model proposed in this study with a Abs. Max. Error of 8%.

2. Structural details and Experimental Test Setup

The 3DPC bus shelter consisted of 4 separately printed concrete components acting as shells of average thickness of 40mm. The top cantilevered portion is provided with webs to emulate the strut analogy for providing strength in non-grouted state. The 3DPC components have been connected to form a single bus shelter using concrete grout and the voids have been filled with M25 grade concrete to provide necessary stiffness to the bus shelter. (Fig. 1)

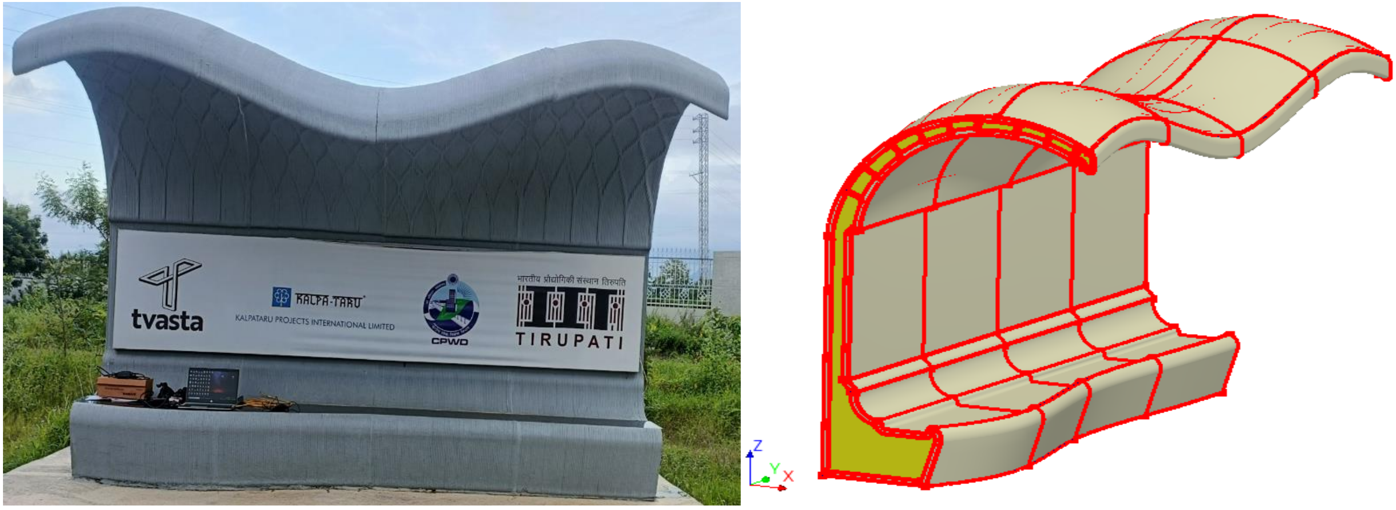

Fig. 1: 3DPC Bus Shelter (a) Actual (b) Model Geometry

Since the geometry of the bus shelter is structurally cantilevered with fixity at the base only, with top portion extending significantly out-of the vertical plane of fixity, the structure was primarily expected and assumed to possess global natural modes in X- direction (weak direction) by virtue of which the number and placement of the sensors utilized for performing AVT were decided. To achieve effective coupling between the surface and the sensors, the sensors were firmly attached to a metal cube in a triaxial orientation, and the cube was anchored to the structure using an adhesive(flexikwik). The AVT was conducted in three phases or setups to cover all the desired locations for measurement of dynamic properties. The multi-setup approach was necessitated due to the number of desired locations being greater than the number of available sensors(accelerometers). A total of 13 locations were identified where sensors in all the three global (x, y, z) directions were placed. Along the elevation, 12 sensors (3 sensors each, at 4 locations) were placed at a height of 30 inches from the base level of the bus shelter i.e., at the plane of changing cross-sectional thickness. Another set of 12 sensors (4 locations) were placed at the onset of the curved cantilever portion of the bus shelter. On top of the projected cantilevered portion, another set of 12 sensors (4 locations) were used to record the measurements. A set of 3 sensors (single location) were adopted as reference sensors in such a way that this location acts as a central point devoid of any local mode deformation/disturbance and the other roving sensors equally distant from it as far as possible (Fig. 2). The sensors employed had a sensitivity of 2.3 V/g. The recording captured ambient noise, primarily from wind loads, intermittent vehicular movement nearby and constant vehicular traffic on the highway a few hundred meters away, over a 30-minute period with a sampling frequency of 300 Hz. The field measurements involving acceleration-time data were post-processed for deriving dynamic properties of the system by performing modal analysis using commercial software package Artemis Modal[7].

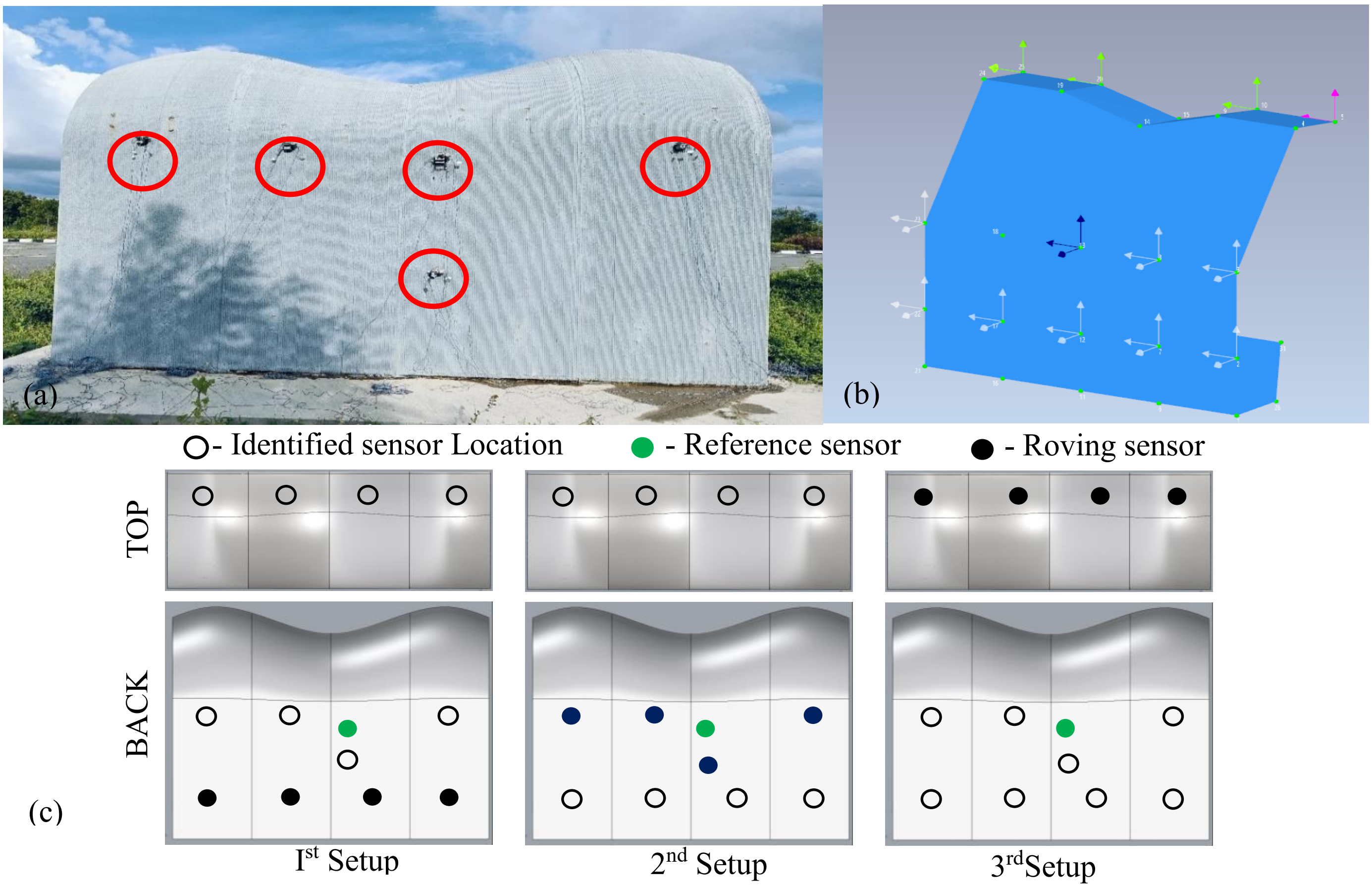

Fig. 2: Sensor placement: (a) Real Structure (1 setup), (b) Artemis Modal Geometry (All 3 setups), (c) Sensor placement layout (Each setup)

3. Numerical modelling

Fig. 3: Meshed geometry of 3DPC Bus Shelter

This study used the commercial software package Rhinoceros 8[8] for solid modeling or the geometry creation of the 3DPC structure and used DIANA 10.9[9] for nonlinear finite element (FE) simulations of the imported geometry. The solid geometry was subsequently converted to a non-linear Finite Element model by defining shape properties, element geometries, support conditions, connection interactions between 3DPC and conventionally casted concrete components, load application, constitutive material properties and the mapped mesh properties.

Fig. 3 shows FE model and simulated elements in 3DPC bus shelter. A mesh convergence analysis was carried on numerical model of the bus shelter to ascertain the appropriate mesh size for the two geometries. In concordance the mesh convergence analysis, an element size of 50mm with tetrahedral/triangle shaped elements was opted for bus shelter.

The boundary condition was defined as a fixed one at the base with translations and rotations in all the three global axes-x, y, z restricted.

3.1. Material Models

This study adopted the concrete damage plasticity model wherein the compressive behavior of the concrete was assumed to form a parabolic softening hardening variation as suggested by Feenstra et al. (1993)[10], [11], [12].

The tensile response of the structures was modelled as a non-linear exponential tension softening behavior. The concrete material upon attaining its tensile strength starts to develop cracks and propagate further to undergo softening. In this model, the stress decreases exponentially with increasing strain at a rate governed by parameter α which is given by;

$$\alpha = \int_{0}^{\infty} y(x)dx = \int_{0}^{\infty} exp(-x)dx = \left[-\exp(-x)\right]_{0}^{\infty} = 1 \tag{1}$$

The corresponding crack stress and ultimate crack strain is given by the following equations, respectively;

$$\frac{\sigma_{nn}^{cr}\varepsilon_{nn}^{cr}}{f_t} = exp\left(-\frac{\varepsilon_{nn}^{cr}}{\varepsilon_{nn.ult}^{cr}}\right) \tag{2}$$

$$\varepsilon_{nn.ult}^{cr} = \frac{G_f^I}{hf_t} \tag{3}$$

Table 1 gives the material properties used in the FEM based numerical modelling of 3DPC bus shelter.

Table 1: Material properties of 3DPC Bus Shelter

Material Input parameters	**Units**	**3DPC Bus Shelter**	
		Grout	**3DPC**
Elastic Young's Modulus	N/mm^2	25000	12500
Poisson's ratio	-	0.15	0.1
Mass density	kg/m^3	2200	2000
Tensile Strength	N/mm^2	2.5	2.0
Tensile fracture energy	N/mm	0.07	0.05
Compressive strength	N/mm^2	25	20
Compressive fracture energy	N/mm	3.6	4.0

4. Results and Discussion

4.1. Experimental Test results

The AVT carried out on the bus shelter emphasized the coupled X-Z direction as the Ist mode shape at a fundamental frequency of 7.6 Hz followed by a torsional Z directional local mode at 12.6Hz and X predominant mode at 25Hz. These modes are predominant because of the cantilevered geometry of the structure with curved part extending significantly out-of-the plane of the base fixity. At higher frequencies, the structure exhibits the similar deformation trends/mode shapes, however, with a larger amplitude. This suggests that the shape(geometry) of the structure exhibits a predominant role in defining the mode shapes and corresponding failure patterns in such structures. The mode shapes at higher frequencies also indicate the effect of cross-sectional thickness variation of the structure. The stress concentration just at the onset of the reduced cross section above the seat of the bus shelter clearly indicates the location of the crack formation in the structure with deformations throughout the length to form a collapse mechanism.

4.2. Validation of numerical model

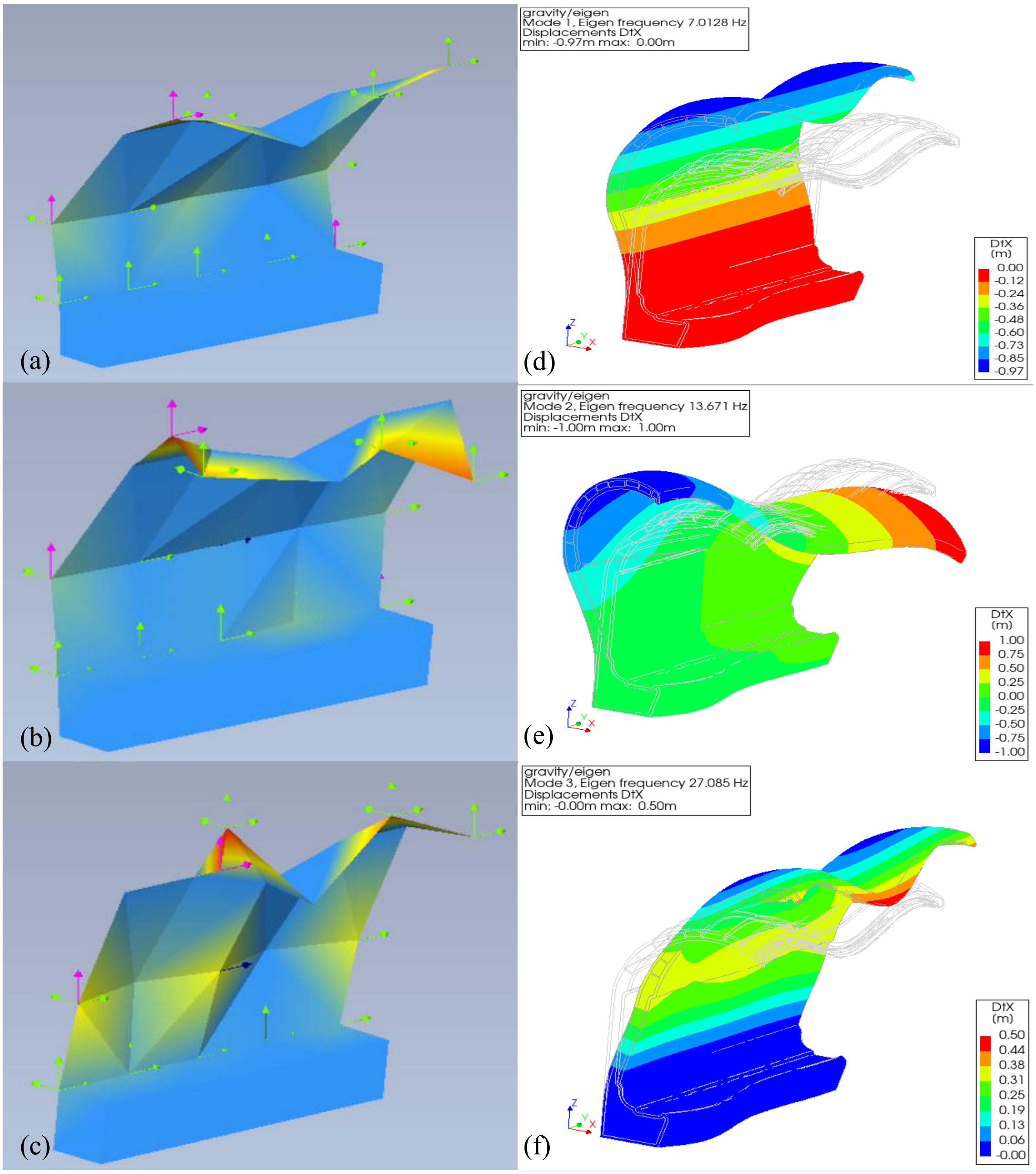

Fig. 4: Comparison of experimental vs numerical mode shapes of 3DPC bus shelter: (a), (b), (c) and (d), (e), (f) are experimentally and numerically obtained 1^{st}, 2^{nd} and 3^{rd} mode shapes, respectively.

The numerical model developed in DIANA FEA 10.9[9] was validated/calibrated against the experimental dynamic properties obtained using AVT. The validating parameters considered were mode shapes and the corresponding mode frequencies. Numerically obtained first, second and third mode frequencies were found to be equal to 7.0Hz, 13.7Hz and 27.1Hz as against experimentally obtained 7.6Hz, 12.6Hz and 25Hz respectively. Table 2 and Fig. 4 compare experimentally obtained mode frequencies and mode shapes, respectively, with those numerically obtained and describes the similarity between the two with an absolute error of 8% and coefficient of correlation as 0.99 calculated using the formula given by;

$$COREL = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \tag{4}$$

where 'n' is the number of modes considered, 'x' and 'y' are the experimentally and numerically obtained frequencies corresponding to each mode, respectively.

Table 2: Experimental vs Numerical Eigen Frequencies of 3DPC Bus Shelter

Mode	Eigen Frequency (Hz)		Cum. Mass Participation (%)		
	AVT	FEM	X	Y	Z
1	7.6	7.0	28.5	0	6.6
2	12.6	13.7	28.5	5.4	6.6
3	25.0	27.1	46.9	5.4	16.4
	Max. Abs. Error (%) = 8.3				

4.3. Lateral Load Capacity and Failure modes

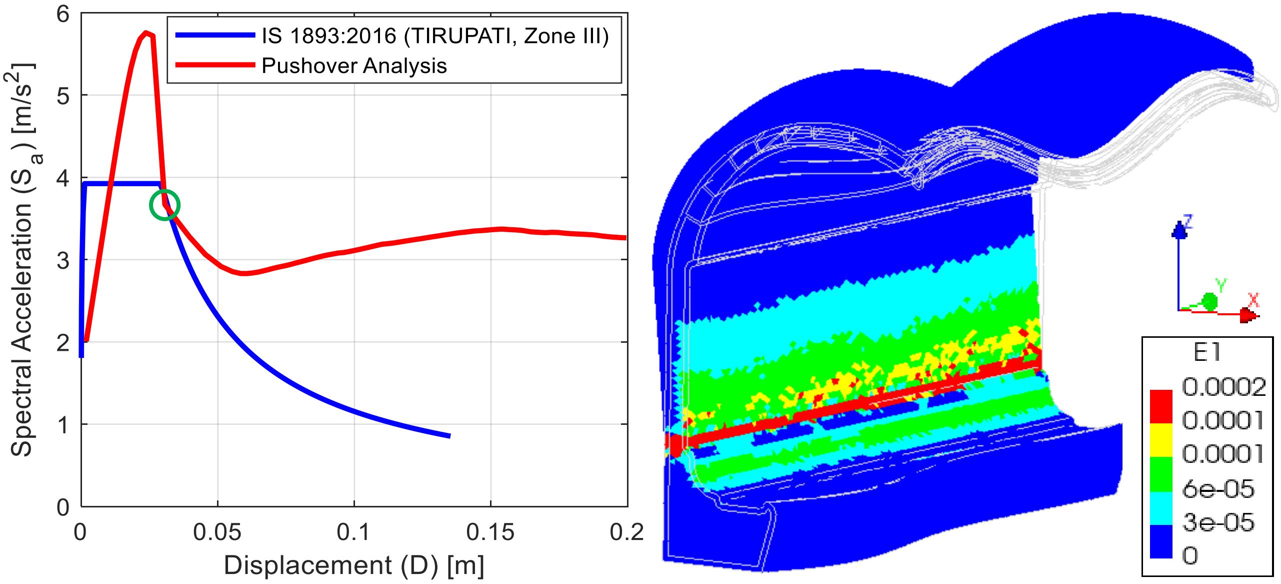

Fig. 5: (a) ADRS Capacity vs Demand Curve (b) Principal Strain Failure Mode

Fig. 5 demonstrates the lateral load carrying capacity, seismic demand and corresponding failure mode of the 3DPC bus shelter in out-of-the plane direction. The lateral load capacity of the structure was estimated using non-linear pushover analysis carried out in DIANA 10.9[9]. Subsequently, Acceleration Displacement Response Spectrum (ADRS) analysis was performed to draw a comparison between the seismic capacity and demand of the structure. The structure performs substantially well in the linear state by exceeding the demand, however, it falls below the demand level in non-linear zone along the out-of-plane direction corresponding to the seismic demand guidelines conforming to IS1893:2016 (Zone III, Indian city). The corresponding failure state of the structure at the intersection point (circled in green, Fig. 5a) of demand and capacity in the ADRS plot can be realized by the principal strain contour (Fig. 5b). The 3DPC structure showed the failure by localized crack propagation throughout the length of of the structure, initiated at the section identified by the abrupt cross-sectional thickness reduction.

5. Conclusion

This study investigated the structural response of a 3DPC bus shelter situated at IIT-Tirupati, India and presented a finite element-based systems level numerical modelling approach using DIANA 10.9 software package[9]. The proposed numerical model was calibrated using dynamic identification of the structure facilitated by the ambient vibration test conducted on the structure. The calibrated model was then used to estimate the lateral load capacity of the 3DPC structure along its weak axis by performing non-linear pushover analysis. The investigation indicated that this structure is governed primarily by its geometry with stress concentrations developing at the critical section of cross-sectional thickness decrement just above the seat of the 3DPC bus shelter. The cross-sectional decrement compromises the lateral load carrying capacity of the structure. This study having proposed the structural performance investigation approach of the built structure in addition to the development of systems level numerical modelling approach can be embarked upon to understand the systems behaviour of similar structures. The study concluded that while the 3DPC technology has potential to produce structures exhibiting architectural elegance coupled with structural safety, thorough design norms and guidelines are required to be framed and exercised while designing structures using this technology. Furthermore, interface-based or discrete modelling approaches may be investigated for system-level modelling of 3DPC structures as significant disparity in strength and stiffness characteristics between 3DPC and conventionally casted concrete have been found at the material level.

Acknowledgements

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