

## Uniqueness & Elegance of Irregular Structures

Alok Panday

(Elegant Consulting Engineers, Ghaziabad, India)

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**Abstract:** World is witnessing the era of innovations where concept of architecture and structural engineering is also getting modernized. The trend now is shifting towards the irregular structures to add altogether a different elegance to the structures. Khalsa Heritage Complex at Anandpur Sahib, Punjab is one of the structures across the globe which depicts the extent till which the modernization of the structures can be done by providing irregular shapes to the buildings. The project has been acknowledged as 'eighth wonder of world' and 'ajooba project' across the country. The project has been developed in about 70 acres of land where built-up area of the buildings is approximately 25,000m<sup>2</sup>. The project primarily has been divided into three building complexes i.e. Complex 'A', 'B' & 'C'. The pedestrian arch bridge along with an artificial water body at ground level adds further elegance to the complex. The part of small existing hillocks at the site, which had to be cut during constructing various structures, were rebuilt to the same surface profile using the concept mechanically stabilized earth using geogrids as soil reinforcement. The complexity and irregularity of the shapes & geometry of various structures created much more challenges than expected while designing and detailing the structures. The reward, in return, was the professional satisfaction and learning experience which crossed all the limits. The present paper describes the salient features of the project along with the structural system, design parameters, design methodology and detailing adopted for the various structures of the project.

**Keywords:** Arch bridge, Artificial water body, Heritage structures, Irregular buildings, Precast canopy, Seismic design

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### I. INTRODUCTION

The Complex primarily houses three building complexes i.e. Complex 'A', 'B' and 'C' (Fig. 1 & Photo 1). Complexes 'A' and 'C' are situated over two separate hillocks and the link between them is provided by a pedestrian arch bridge to make the disparate buildings a cohesive unit. The outside surfaces of the buildings and vertical side-walls of the arch bridge have been stone cladded to blend the elegance of traditional monumental structures to modern structures. At some places i.e. inside surfaces of the buildings, soffit of the arch bridge etc. the concrete surfaces have been kept exposed without any cladding to exploit the potential aesthetics of the fair-faced concrete. The various complexes consist of the following:

- Complex A: Housing library, auditorium, temporary exhibit gallery etc. Part 4 of this building rests over an arch bridge which is spanning between the two hillocks spaced at a distance of about 26m.
- Complex B: Consisting of the pedestrian arch bridge, cafeteria, kitchen block and the artificial water body. The disciplines of structure and architecture truly merge in the presence of reflecting pool beneath & precast canopy over the bridge.
- Complex C: Housing permanent exhibit building, heritage museum, media exhibit building and an entrance lobby.

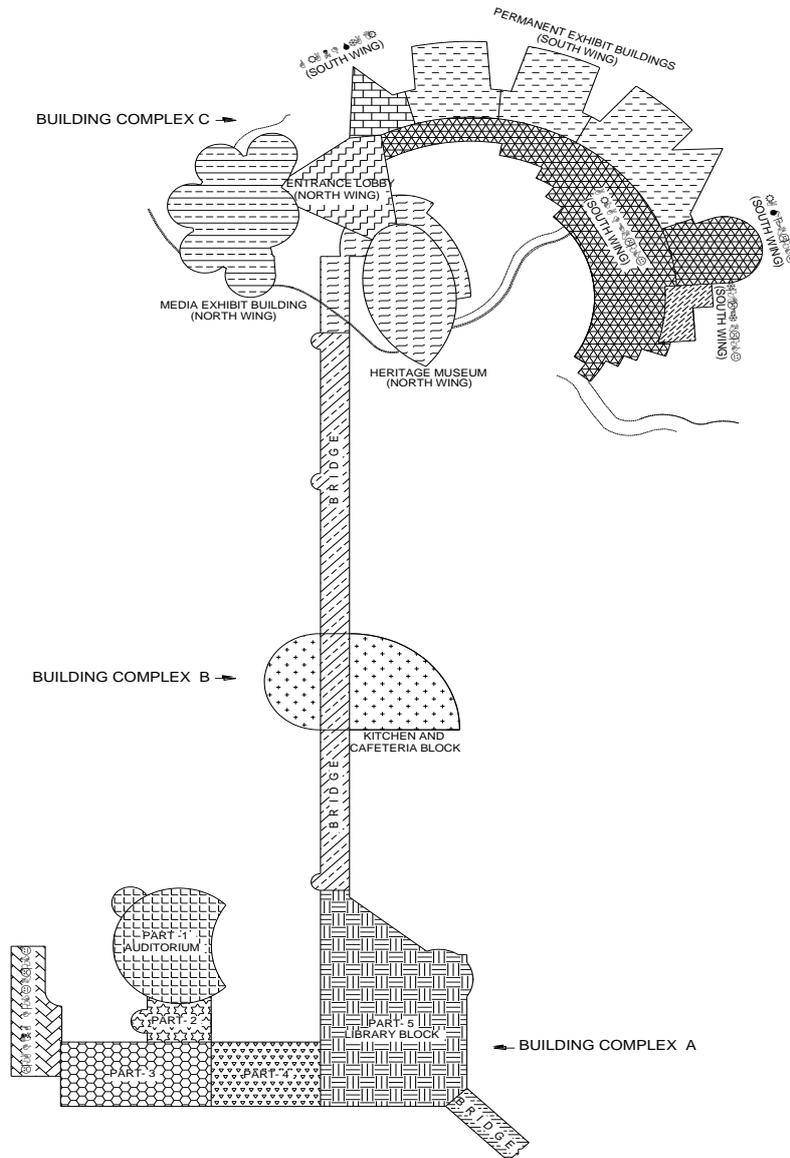


Fig.1. Key plan of the Khalsa Heritage Complex

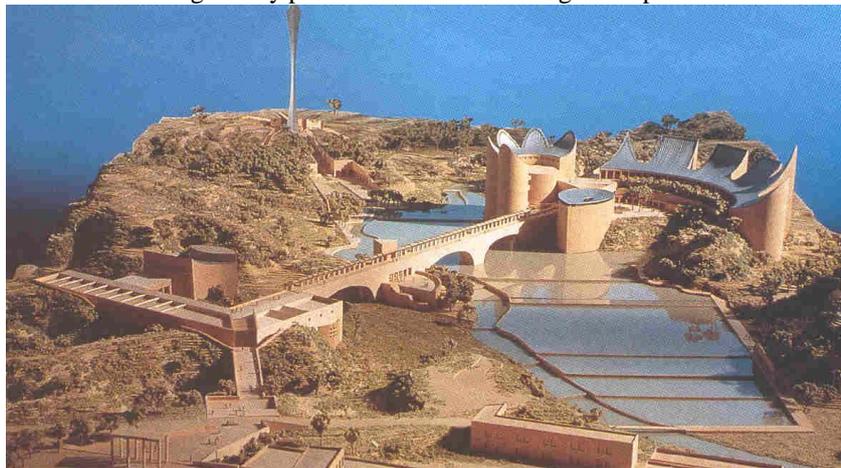


Photo 1 Model view of the Khalsa Heritage Complex

## II. DESCRIPTION OF STRUCTURES

Various structures of the complex comprise different structural forms depending upon their usage, functional and architectural requirements.

### 2.1 Complex A

Complex 'A' (Fig.2) houses reception, temporary exhibit gallery, meeting rooms and mechanical areas in addition to library stacks.

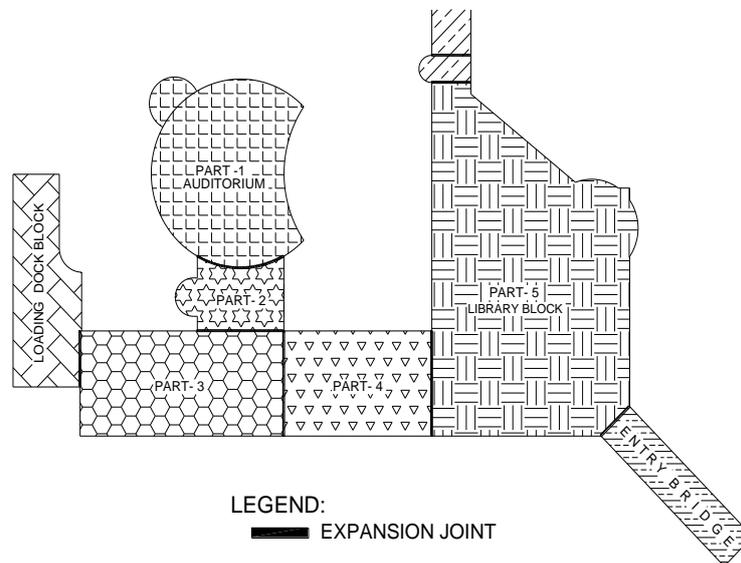


Fig.2. Typical plan of Complex 'A'

Part 4 of the complex is required to bridge two adjacent hillocks at a distance of approximately 26m where an arch bridge consisting of 3 arch ribs has been provided to support the floors at different levels. Remaining structure is conventional cast-in-situ structure.

The auditorium houses a lounge and mechanical Areas in addition to two level seating and stage. While the floors are planned as conventional cast-in-situ R.C.C. beam, slab structure the large span (~18m x 18m) roof over seating area is having one way closely spaced ribbed slab with the rib spacing of approximately 1.5m spanning longitudinally.

### 2.2 Complex B

The pedestrian arch bridge, located in Complex 'B', is about 170m long and 7m wide. The bridge comprises of four numbers of independent reinforced concrete arch bridges, three with a span length of 33m & one 27m (Fig.3). The rise of central axis at crown is approximately 9.8m above springing level. The individual arch bridges have been provided to facilitate the independent construction of each arch bridge and allow for reuse of formworks. These bridges have been made independent by providing prestressed concrete tie beams (four numbers in each bridge) at springing level to carry the horizontal thrust transferred from the arch rib and making the foundations free of this thrust (Photo 2). Each arch bridge has 7m wide single arch rib supporting 250mm thick side walls at the edges, which finally support the deck slab. Thickness of arch rib varies from 300mm at crown to 500mm at springing level. The arch bridges have been separated out by an independent deck slab (about 5m long) resting over the corbels projecting from end wall of the bridges (Fig.3 & 4 and Photo 3). A semicircular balcony projecting out from the independent deck slab serves as a look out area (Fig.3). The deck slab has a uniform thickness of 300mm.

The smaller arch bridge (27m span) has a cafeteria at springing level & service floors at intermediate levels between arch rib & deck slab (Fig.3). About half of the bridge at deck level is covered with canopies placed at the top of the deck (Photo 4).

To have high quality fair faced concrete, precast canopies have been provided which are fixed to the pocket left in the bridge deck using early high strength non-shrink grout (Fig.5). In order to simply the erection and placement of the single piece of the precast canopy (Photo 5), the individual piece of the canopy was divided

into three different segments (i.e. column, slab & cap) which were assembled together while erecting the canopy over the deck (Photo 6).

Cafeteria and kitchen blocks (Photo 4) primarily consist of cafe dining room, kitchen, lobby, receiving room, washrooms and mechanical/electrical rooms. The structural system proposed for the building is framed structure having conventional cast-in-situ R.C.C. beam and slab floors.

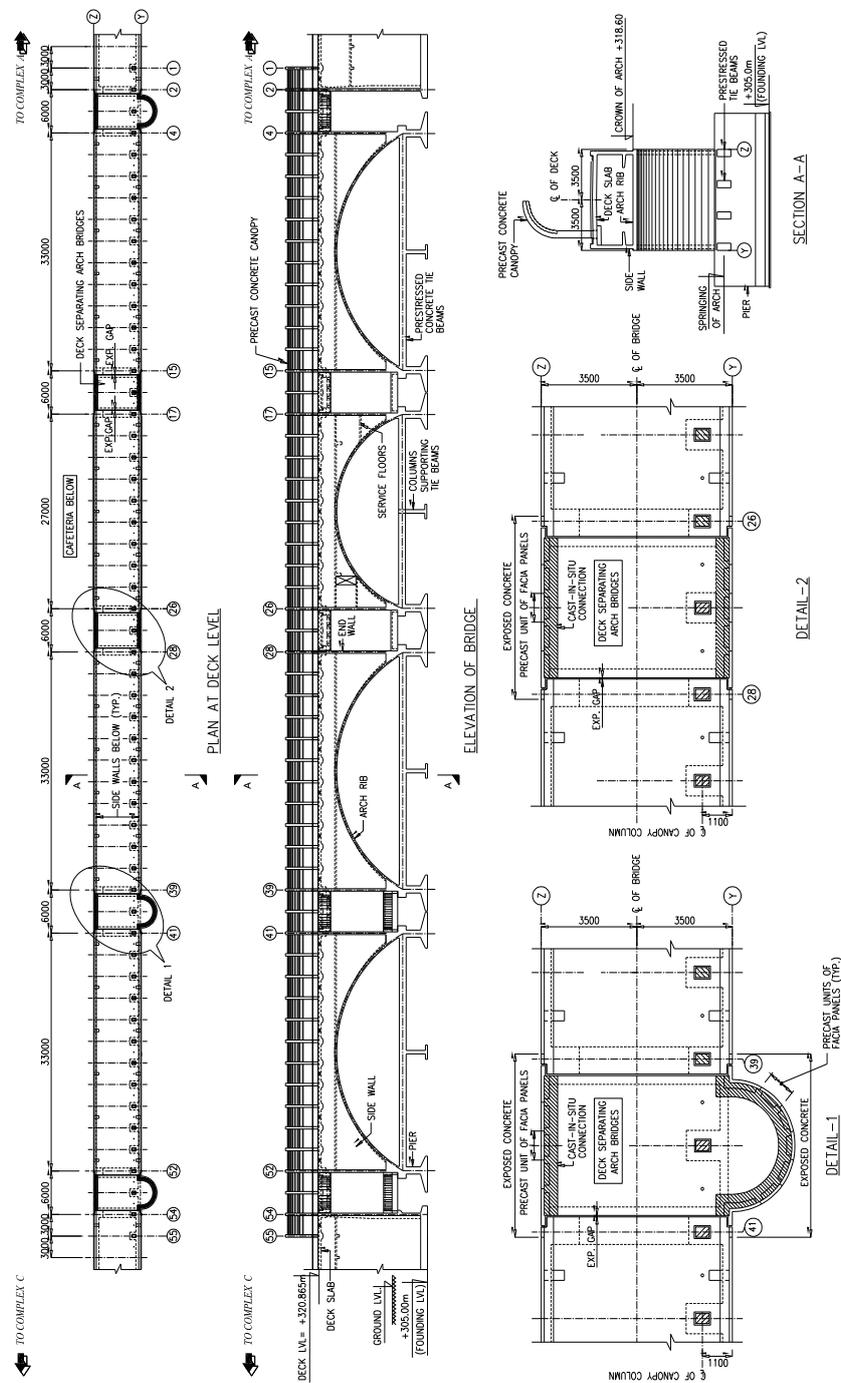


Fig.3. General arrangement of the pedestrian arch bridge



Photo.2. Construction of prestressed tie beams at springing points under progress

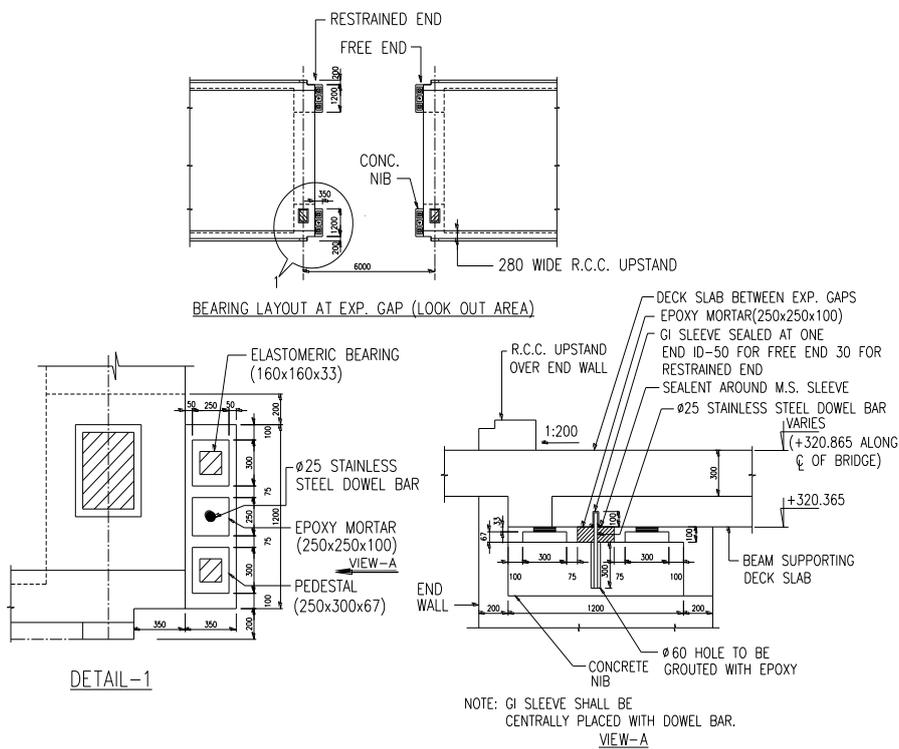


Fig.4. Support arrangement for intermediate slab between two arch bridges



Photo.3. Independent slab separating two arch bridges



Photo.4. Precast canopy over deck and cafeteria block

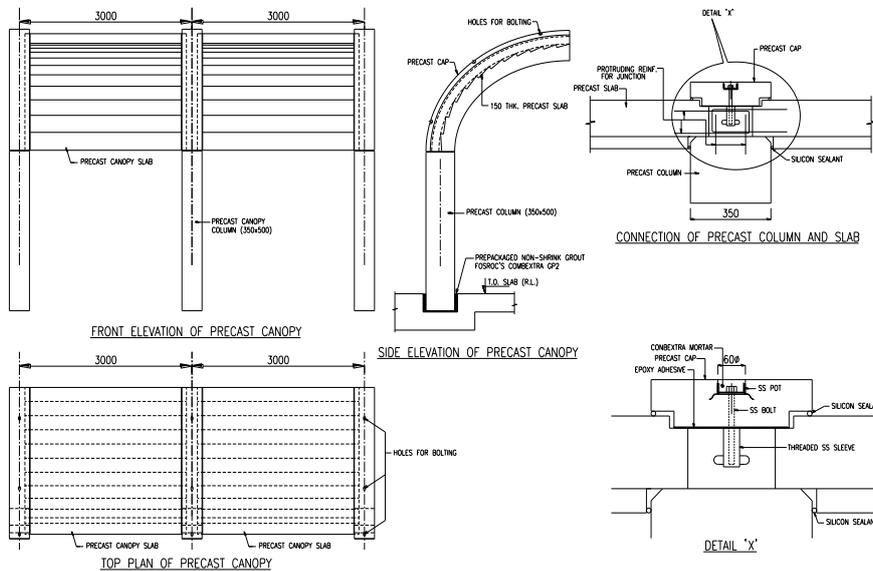


Fig.5. Details of precast canopy over pedestrian bridge



Photo.5. Mockup of single piece of precast canopy difficult to handle



Photo.6. Mockup of three pieces of precast canopy to simplifying handling

### 2.3 Complex C

This complex is subdivided into two wings i.e. north wing and south wing. North wing houses heritage museum, media exhibit building and an entrance lobby whereas south wing houses permanent exhibit buildings (Fig.6 & Photo 7).

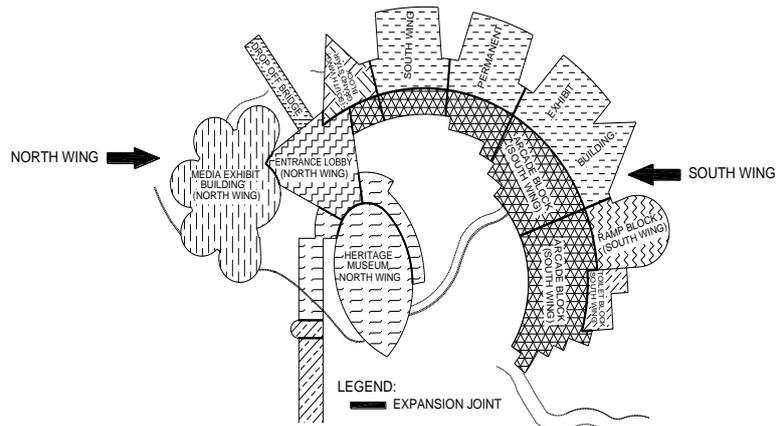


Fig.6. North and south wings of Complex 'C'

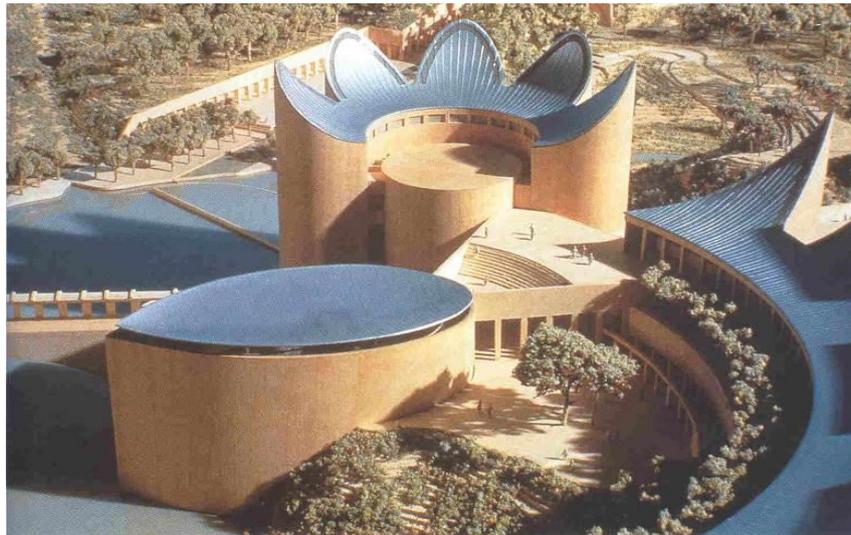


Photo.7. Model view of the Complex 'C' showing north wing

Heritage museum which is in the shape of a boat, mainly houses a multilevel ramp in the central part which goes up till a height of about 16.5m and from where images projected on the walls of the heritage museum can be seen (Photo 8). The long span roof of the building is filled with water at the top to get the reflecting effect. The structural system consists of R.C.C. shear wall structures. Due to long span of the ramp inside the building, the same was made of prestressed concrete.

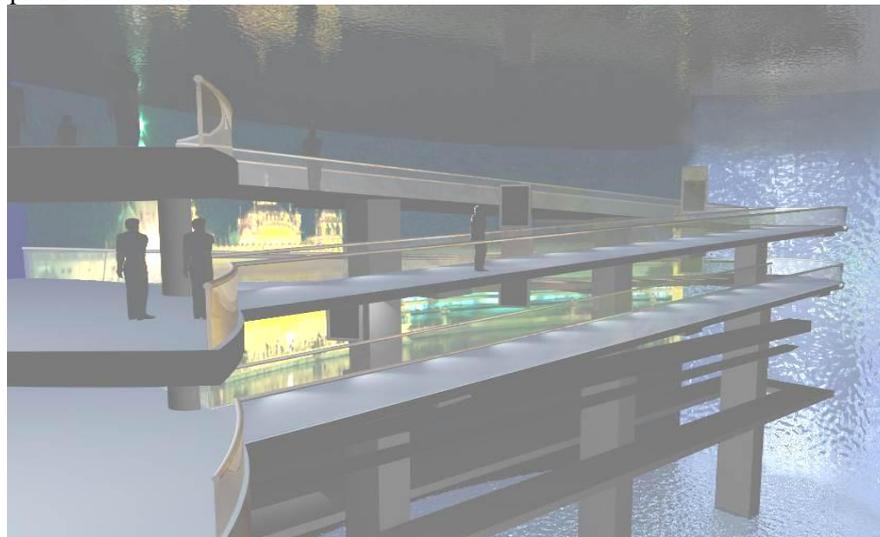


Photo.8. Model view of multilevel ramp inside the heritage museum

Media exhibit building mainly consists of mechanical space, introductory media exhibit space, coat rooms, toilets, control room and exhibit galleries. The structural system is R.C.C. frame- shear wall structure with conventional cast-in-situ beam and slab floors except in media exhibit space (i.e. in central part) where coffer slabs are provided due to depth limitations. The presence of a considerably large central opening at some of the floors required provision of a very irregular arrangement (i.e. radial and circumferential) of the beams in the slab (Photo 9) The structural system for the entrance lobby is framed structure having roof of the lobby as triangular coffer slab arrangement (Photo 10).



Photo.9. Provision of very irregular pattern of beams due to central opening



Photo.10. Model view of triangular coffer slab in the entrance lobby

Permanent exhibit building consists (Photo 11 & 12) of arcade, receiving dock, mechanical / electrical room, reception, storage space, workshops and labs, lecture and meeting space, book store, gift shop, offices, launch room, toilets, exhibit galleries, planters and grand stair. The structural system proposed is R.C.C. frame- shear wall structure, which consists of floors mainly with coffer slab arrangement due to depth limitation. The long span curved roof of the building is planned as closely spaced ribbed slab with rib spacing of approximately 1.5m.



Photo.11. Construction of south wing nearing completion



Photo.12. Construction of south wing nearing completion

The part of small existing hillocks at the site, which had to be cut during constructing various structures, were rebuilt to the same surface profile using the concept mechanically stabilized earth using geogrids as soil reinforcement (Photo 11 & 13).



Photo.13. Remaking of hillocks using geogrids as soil reinforcement

### **III. STRUCTURAL CONFIGURATIONS**

As per the codal provisions, the irregular structural configurations in plan as well as in elevation should be avoided. In case they are unavoidable, the building portions should be separated in such a way that the extent of irregularity in each building block separated by consecutive expansion joints does not exceed the limits specified in the code.

The locations of expansion joints had therefore been fixed up keeping in view the above-mentioned aspects. For example, expansion joints had separated various portions of permanent exhibit building. Similarly, the building portions having lesser height than the adjacent taller building portions had also been separated with the help of expansion joints. Although, structure adherence to the norms of code was not possible completely, an attempt was made to adhere to the code in terms of building configuration as far as possible. Clear width of expansion joint was fixed as 50mm for separating the different block of the buildings.

### **IV. STRUCTURAL MODELING**

Three dimensional space frame grillage models were prepared for analyzing various buildings and pedestrian arch bridge (Fig. 7 to 9).

Two different space frame grillage models (Fig 7) were prepared to examine the true behavior of the arch bridge under various loading conditions. In these models, foundations were represented by equivalent vertical, horizontal and rotational springs to take advantage of the flexibility of the foundations while calculating the forces due to the global temperature changes. First model was, prepared for construction stage analysis, consisted of structural elements representing foundations, piers, prestressed tie beams and arch rib only. Loads such as weight of walls over arch rib; weight of formwork and erection live load (for walls and deck slab) and weight of deck slab were applied to this model in addition to the selfweight of structural elements present in the model. The second model representing all the bridge elements was prepared to study the bridge behavior under service condition. All other loads acting during service stage of bridge such as superimposed dead load, live load etc. and reverse weight due to formwork and erection live loads (considered during construction stage analysis) were applied to this second model. Results of both the models were then superimposed to get the final forces in the foundations, piers, tie beams and arch rib. Walls over arch rib and deck slab were designed for the forces obtained from the service stage model. In the case of arch bridge with span length of 27m, the additional effects due to presence of intermediate service floors and large openings in the arch rib and walls were studied by adding/ deleting grillage members while preparing the structural model for the bridge.

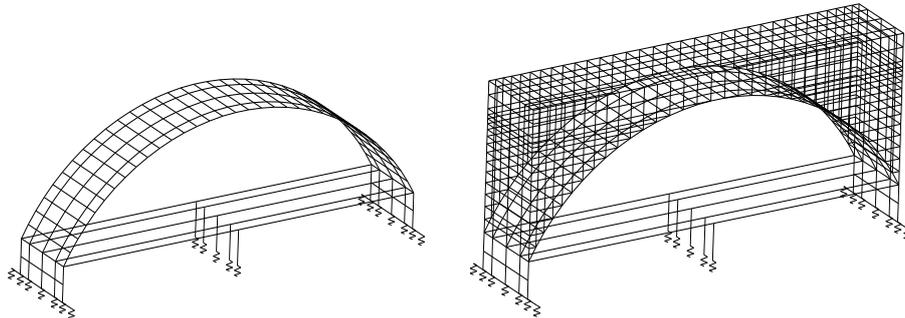


Fig.7. Construction stage and service stage models for the arch bridge

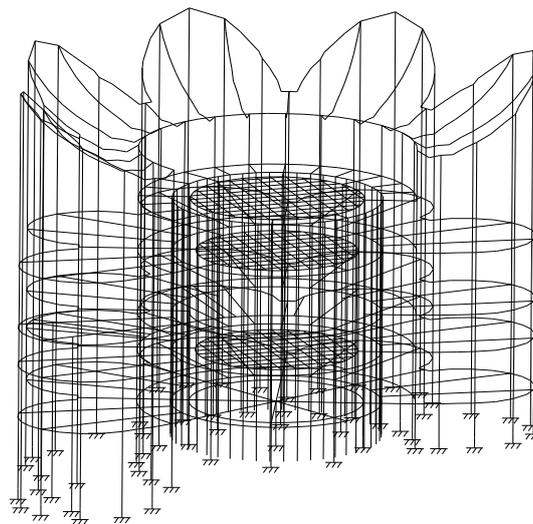


Fig.8. Structural model of media exhibit building

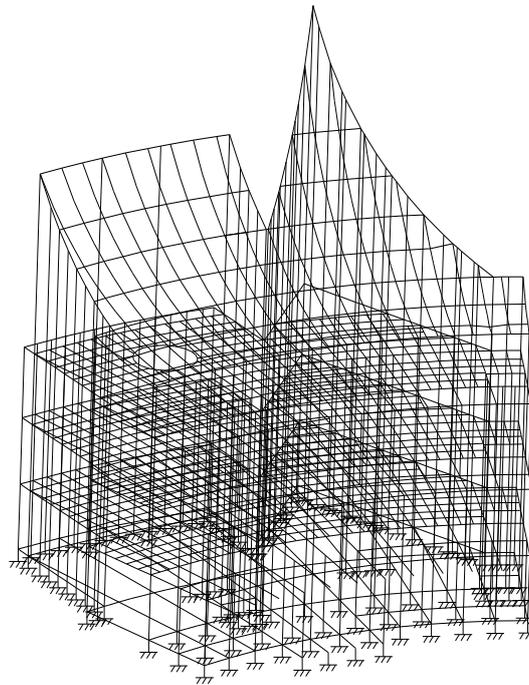


Fig.9. Structural model of part of permanent exhibit building

#### **V. DESIGN OF THE PEDESTRIAN BRIDGE**

The pedestrian bridge was designed based on the working stress method based on the provisions of IRC codes for the following load:

- Dead load is the self-weight of structural elements were calculated on the basis of unit weight of concrete as  $2.5 \text{ t/m}^3$ .
- Superimposed dead loads primarily consisted of weight due to 100mm thick deck surfacing, precast parapet and precast concrete canopy (about 10 t) at a spacing of 3m.
- Live load is a pedestrian live load of  $500 \text{ Kg/m}^2$  was considered. The bridge was analyzed with two conditions of live loads i.e. full span loaded condition and half-span loaded condition.
- Temperature variations of  $\pm 25^\circ\text{C}$  was considered as per the requirement of the code.
- Shrinkage strains in concrete, which cause the arch rib to shorten, were considered for simplicity as being equivalent to a fall of temperature.
- Differential settlement of supports of foundations was taken into account by reducing the value of spring constants of one foundation to half as compared to other foundations.
- In Seismic forces, a static analysis was performed to visualize the effects of seismic forces. Seismic loading was considered for static effects of  $0.144g$  as per the code.

#### **VI. DESIGN OF THE BUILDINGS**

The buildings of various complexes were designed based on the provisions of the BIS codes for the following load combinations:

- $1.5*DL + 1.5*LL$
- $1.5*DL \pm 1.5*WL/EQ$
- $1.2*DL + 1.2*LL \pm 1.2*WL/EQ$
- $0.9 DL \pm 1.5 WL/EG$

**Note:** 1. 50% of LL was considered when combined with WL or EL  
2. In combination 4, the earthquake forces were considered only on the DL)

As the project was located in high seismic zone, ductile detailing of the various structural components were done as per the provisions of IS: 13920-1993.

Due to irregularities of the geometry and shape of various structures, specific attention was required to be paid while detailing the structures. As an example, foundation layout plan of the media exhibit building and heritage museum is in Fig. 10 where different hatch shows foundations at different level or having different thickness.

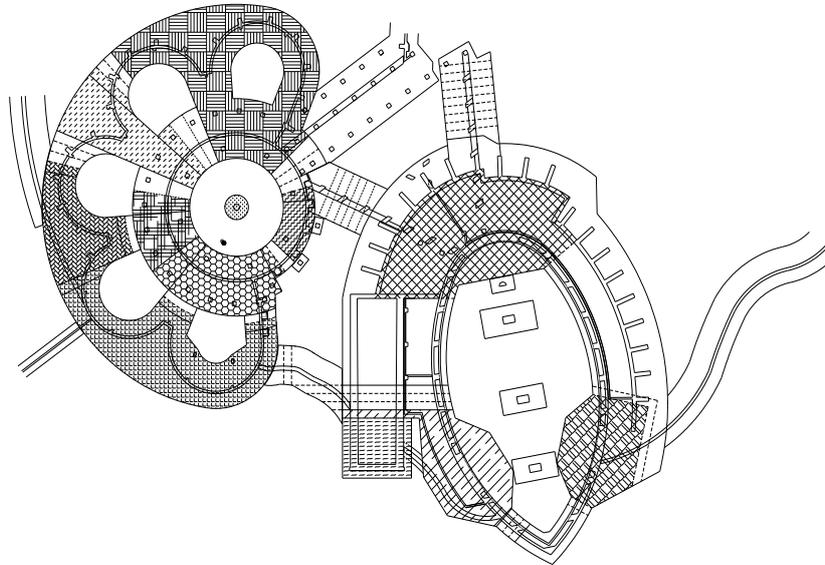


Fig.10. Foundation layout plan of the media exhibit building and heritage museum

## VII. CONCLUSIONS

The modernization of structures is taking place across the globe in terms performance, complex geometry and shape of the structures. Though availability of the reliable software has made the analysis of structures relatively simple and easy, it still requires thorough understanding of the subject and sincere efforts specifically in case of structures such as Khalsa Heritage Complex (Photo 14). The complex which has gained wide popularity internationally required sincere efforts not only at design stage but also at all stages starting from the beginning till completion of the project. Detailing of various structural components and achieving high quality surface finishing required specific attention during design and construction stage respectively.



Photo.14 Completed view of Khalsa Heritage Complex, Anandpur Sahib, Punjab

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