STRUCTURAL ENGINEERING

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OF
STRUCTURAL ENGINEERS

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VOLUME 15-4

Oct-Nov-Dec 2013

CIDCO EXHIBITION & BUSINESS CENTRE AT VASHI, NAVI MUMBAI

(See Pg 3)

STRUCTURAL ENGINEERING - AN ART OR SCIENCE ?
PART 1

(See Pg 22)

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Contents

Editor : **Hemant Vadalkar**

Fraternity News

WELCOME TO NEW MEMBERS

(JUL, AUG, SEP 2013)

M	1312	Harshad B. Patil
M	1313	Yogesh G Modha
M	1314	Boobathiraja Sukumar S.
M	1315	Rajesh R. Kohli
M	1316	Jiyalkumar N Chaudhari
M	1317	Ravikumar Rangasamy
M	1318	Vasudev R. Upadhye
M	1319	Vidyapathi P
M	1320	Nitin C. sanklecha
M	1321	Tushar Y. Dawda
M	1322	Nikhil Kulkarni
M	1323	Deepak R Sane
M	1324	Ram N Singh
M	1325	Qamruddin Abdul Remman Bhoira
M	1326	Rajendra D Mudkhanna
M	1327	Yogesh S Bamane
JM	32	Nikita Pankaj Kulkarni

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Organisation Member : 23
Sponsors : 8
Members : 1327
Junior Members : 32

TOTAL STRENGTH 1422

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- Computer Software
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- Rehabilitation of Structures
- Construction Technology & Management
- Geo-Tech & Foundation Engineering
- Environmental Engineering
- Non Destructive Testing
- Bridge Engineering
  & Other related branches

AIMS & OBJECTIVES

1. To restore the desired status to the Structural Engineer in construction industry and to create awareness about the profession.
2. To define Boundaries of Responsibilities of Structural Engineer, commensurate with remuneration.
3. To get easy registration with Governments, Corporations and similar organizations all over India, for our members.
4. To reformulate Certification policies adopted by various authorities, to remove anomalies.
5. To convince all Govt. & Semi Govt. bodies for directly engaging Structural Engineer for his services.
6. To disseminate information in various fields of Structural Engineering, to all members.

CIDCO EXHIBITION & BUSINESS CENTRE AT VASHI, NAVI MUMBAI

P. S. Badrinarayan

CIDCO Ltd , who are the statutory planning authority for Navi Mumbai, proposed in 2008 to build a permanent Exhibition Centre in Navi Mumbai and chose a very strategic location near Vashi Railway Station and just adjacent to Sion-Panvel Expressway. The complex comprise of Exhibition Centre and a Business Centre with Auditorium, which are linked by a pedestrian footbridge to allow for seamless movement through the 2 centres. The overall view is as seen in Fig 1a,1b & 1c below:

Fig 1c – Overall Rendered view from Sion-Panvel highway side

Fig.1a: Over all view – Architectural Rendering

Fig.1b: Over all view – Under construction

1.EXHIBITION CENTRE STRUCTURE :

Considering the need for an iconic design as desired by CIDCO, the Architect after developing several options in consultation with SPA, concluded on a doubly curved roof that has a wave-like form with varying height roof along the width and length and also the structure was along a curve in plan . The structure was divided into 3 sections across the width, wherein the roof in central section was higher than the outer 2 sections to allow for natural light through the step between the 2 roof levels. On finalising the form, then the shape of steel sections was decided to maintain as Circular, Square and Rectangular Hollow Sections (CHS, SHS, RHS) and limited to max 400mm size in any member. The entire structure is divided into 2 Identical structures with a Expansion joint at the centre (Refer Fig. 2, 3, 4). To cater to the Utility Services (HVAC & Electrical) and other public amenities such as - Toilets, Canteen, Meeting rooms, Entrance & Ticketing, etc.- , Service blocks (total 7 nos) of RCC construction are adjoined with the Exhibition Centre structure, without any structural connection. (Refer Fig 1a)

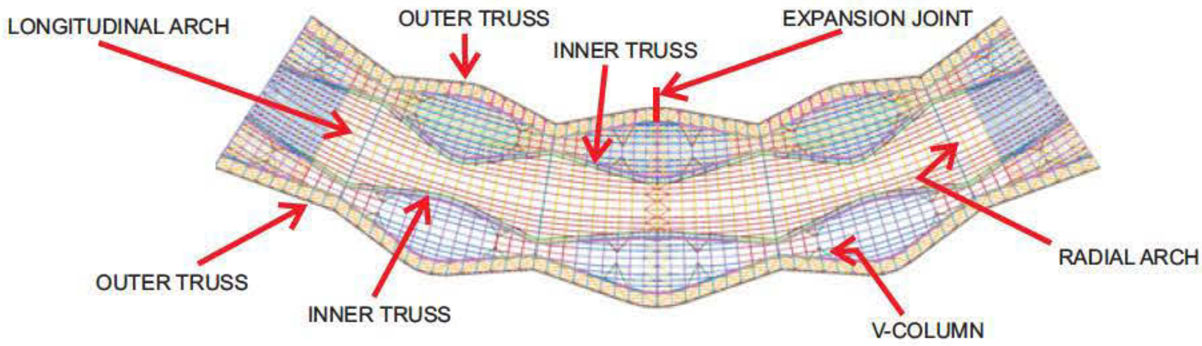

Fig.2: Plan (From TEKLA model)

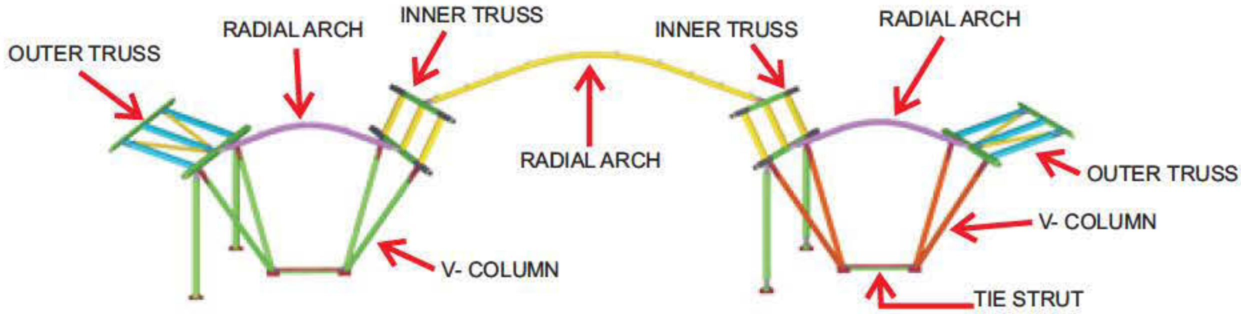

Fig.3: Cross Section (From TEKLA model)

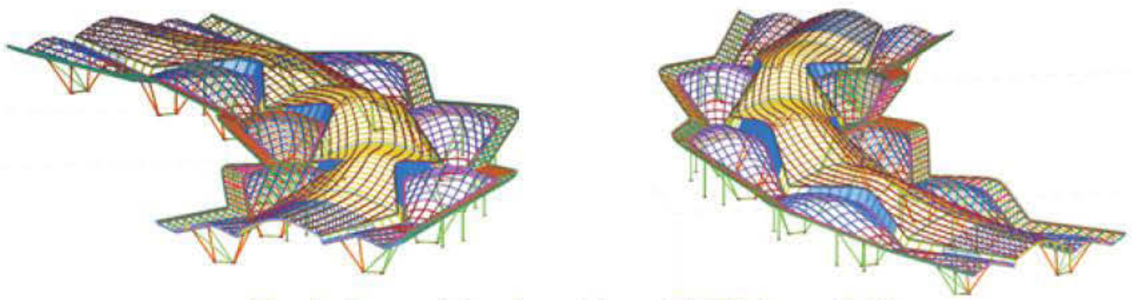

Fig.4: Isometric view (From TEKLA model)

Fig.5: Architectural Rendering – View from outside

The columns supporting the 3 Roof Sections, are V-shape (Chevron) to provide stability and reduce span of trusses above. The c/c of the V-columns is about 40 to 46m at base plate level. Each section of the roof was designed as a 2-way grid comprising of Radial Arch CHS members 400Ø on Radial lines @ 1^{0} c/c, which is about 4.3m to 5.5m c/c and longitudinal Arch RHS members (over the Radial Arch members) at spacing of 2.3 to 3.5mc/c. The span of the Radial Arch in central section varies from 13.5m to 32.5m & in outer sections varies from 6m to 23m. The central roof section was supported on Inner Vierendeel Trusses (Inclined at 66 to horizontal) comprising of SHS 400x400 members (chords & verticals) spanning along a curve between the V-shape columns, and the outer roof sections were supported on the Inner Vierendeel Trusses and an Outer Inclined Truss (inclined at 21 to Horizontal) comprising of SHS400x400 members (chords & verticals) with diagonal CHS members. The two Inner Vierendeel Trusses allowed for fixing Polycarbonate Skylight Panels, for natural day lighting of the Exhibition Halls.

The approximate Arc length of Roof along the c/l of the structure is 314m, and angle subtended by this arc is 66. The total width between ends of Outer Truss varies between 55m – 75m, height of V-columns varies between 7m to 12m height, Height at centre of Radial Arch in Central Section varies from 14m to 19m and on Outer Two Sections varies from 7.5m to 14.5m, Depth of Inner Truss varies from 3 to 5m and depth of Outer Truss is 5.5m constant.

Lateral stability for Gravity loads and Wind loads (which dominate over seismic loads) are achieved by rigid welded connections between Trusses with the Radial Arch and

V-shape columns (Fig. 7, 8, 9 & 16), and additional Vertical members concealed within the Glazing line that form a braced system. Due to inclination of the V-shape columns, the column bases were tied by Box Strut to resist the thrust forces due to Gravity and Wind loads (Fig. 6 & Fig.15). The column base and box struts, being below floor level, are encased in RCC.

Considering the forces and that all the structural elements of the roof align with the skin or the form of the structure, and the limitation in maximum size of members to 400mm, it was decided to use Hot Finished hollow sections of Grade 355 of CORUS make, that was shipped from UK and Japan. The thickness of the hollow sections (CHS/SHS/RHS) varied from 8mm to 32mm. Wherever the steel columns punctured the RCC Slabs of adjoining structures, clear gap of about 50-100mm was maintained, to avoid any connection with such structures. (Refer Fig 26)

Drainage from the 3 roof sections were taken on 4 steel gutters that follow the bottom line of Outer & Inner trusses and collected in 8 sumps at the low points of the Roof Structure, and taken out by RWP(2 nos per sump). The Gutters were fabricated to profile from 6 thk plates with angle stiffeners to provide for fixing of Aluminium gutter and insulation on the inside surface. (Fig. 8,9, 10 & 23).

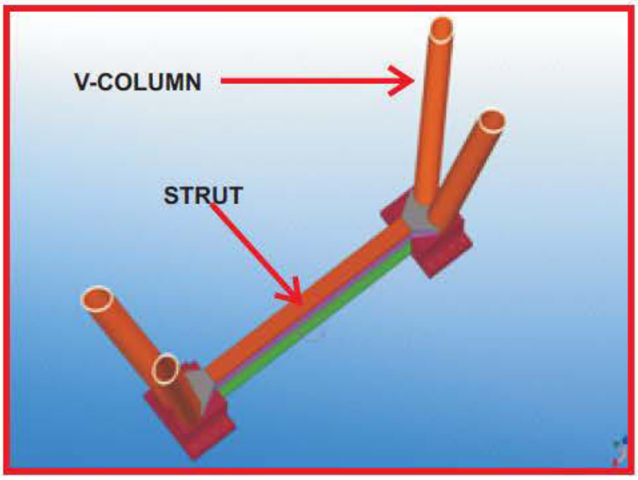

Fig. 6: Column base connection (from TEKLA model)

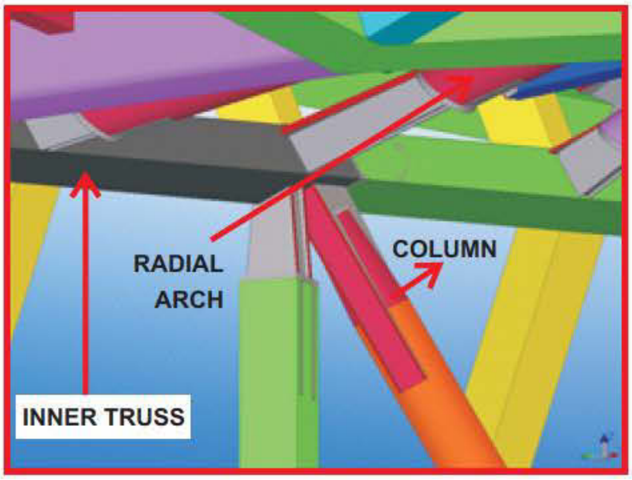

Fig.7: Column- Inner Truss – Radial Arch Connection (from TEKLA model)

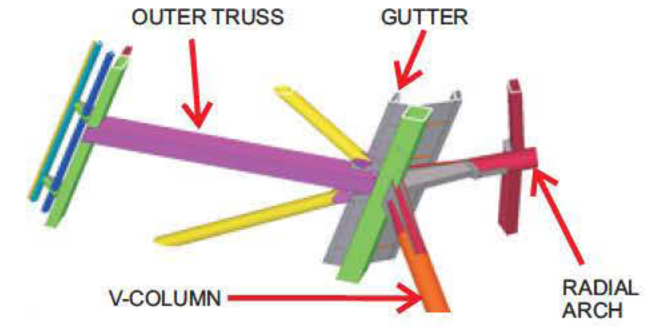

Fig.8: Outer Truss - Column– Radial Arch – gutter connection (from TEKLA model)

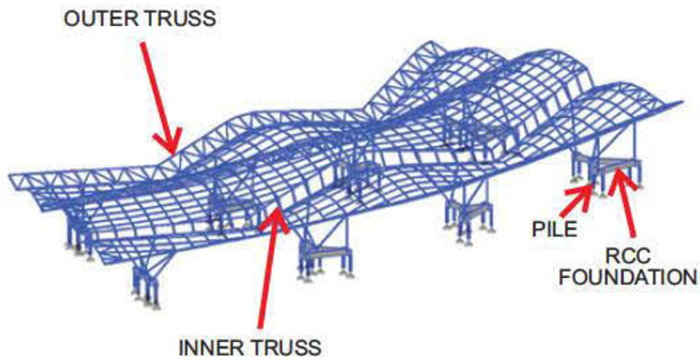

Fig.11: STAAD Analysis model for Half Structure

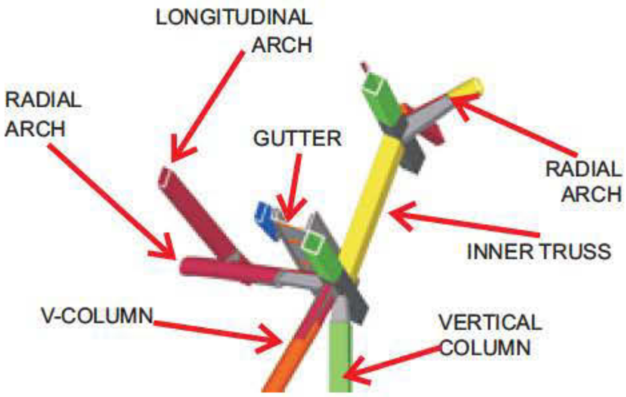

Fig.9: Inner Truss - Column– Radial Arch – gutter connection (from TEKLA model)

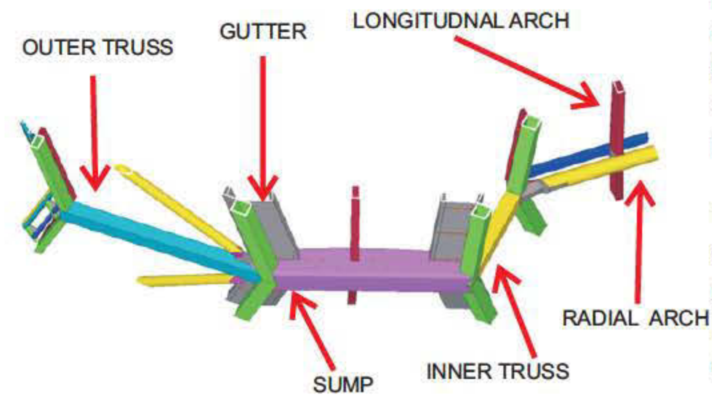

Fig.10: Outer Truss– sump & gutter–Inner Truss – Radial Arch (from TEKLA model) at Low Point.

Vertical Glazing from floor to Roof on the long sides followed the curved profile of Inner truss / Outer truss line as per the Architects drawings, which formed the outer boundary line of the Exhibition Hall space (Fig.5). The glazing was supported on Steel triangular Box transoms (fabricated from plates) ,which were spanning between Taper box columns (fabricated from plates) located on every radial line. The columns were terminated 1.2m below truss to provide clear glass band and therefore supported on Box wind girder at top to act as propped cantilever.

The entire Roof Structure (for one-half) including all RCC substructure & Glazing Structure was modelled in STAAD for analysis & design due to various loads- Gravity Loads, Live loads on Roof, Service Roads below Roof & Wind loads in 2 directions (Fig.11).

The entire structure is supported on Precast pre-bored Pile foundations, with pile caps connected by tie beams of same depth as pile cap, to distribute equitably the thrust forces to the piles, and each such foundation comprising of pile-caps and tie beams was cast in one pour.

The roof structure supports KALZIP Double Skin roof system that comprises of steel decking spanning between Longitudinal Arch members and topped with Insulation and standing seam Aluminium roof that can exactly follow the doubly curved profile. (Fig 21 & 22)

The entire structure with all connections was modelled on TEKLA Steel software due to the complex geometry and all shop drawings were generated from the model. Figs 6 to 10 are extracts from the TEKLA model and Fig 17 shows some connection views from TEKLA model v/v actual views.

Construction of the roof required numerous temporary supports as the trusses (due to the 2-way geometry, curve in plan and along length, and due to its inclination with the vertical) could be erected in panels with field welding at these joints (Fig.14). Only after all welding of all members & testing of field welded joints were completed, the supports were gradually removed (Fig.16).

For the connection of SHS to SHS of the Inner & Outer trusses especially the sections of 32mm & 20mm thickness, the large corner radius of the thicker sections posed a problem for direct butt welding. This was then achieved by cutting out the face of SHS of the top & bottom chords, that was of same footprint as the SHS to be connected, and then welding a plate to achieve a square corner for butt welding – (Refer Fig 12).

Profile cutting of the CHS all the V- columns was achieved by placing a 1:1 drawing of the cutting profile on paper, that was extracted from the TEKLA model , as CNC profile cutting machines were not available at the time.(Refer Fig 13)

Fig 18-22 shows the views of 'under construction' and 'partly covered with decking'.

Painting of all steelwork after shot blasting comprise of sprayed on epoxy primer (shop painted) and finish coat on site using sprayed on polyurethane finish for Internal steelwork within the structure and polysiloxane finish for External steelwork outside the structure. All touch-up of primer after field welding of connections was carried out by suitable compatible primer.

Pedestrian Footbridge, Central Hall , Grand Stair & Public Plaza

A RCC footbridge connecting the Exhibition Centre to the Business centre over an existing road bifurcating the 2 centres was designed to provide seamless access between the 2 centres. On the Business centre, the footbridge was provided with expansion joint and landed at edge of a Public plaza. The footbridge consists of 2 separate walkways comprising of spine beam supported on capsule RCC columns and interconnected by diagonal walkways which thus formed triangular shaped cut-outs between the 2 bridges. (Refer Fig 1a,1b & 24)

The Footbridge continues into Exhibition centre thru the Central Service Block, (Refer Fig 1a), which is a 2 storeyed RCC building and then extends into a Central Exhibition Hall, which is a RCC Flat plate slab at about 5m from Exhibition floor and supported on RCC Circular columns, that spans across the width of Exhibition centre, and finally ends in a Grand stair that is a RCC stair on a truncated conical surface. (Refer Fig 26)

The Public plaza adjacent to Business centre is a RCC flat slab with circular cut-outs / circular offsets in central portion to have reduced thickness in central area and supported on RCC circular columns on a 7.5x7.5m grid . (Refer Fig 1a,1b & 25)

Thus there is a seamless access from the Grand stair on North side thru the Central Hall , Central Block, and thru Footbridge to the Business Centre and Public Plaza on the South side.

Fig - 12 (a)

Fig - 12 (b)

Fig - 12 (c)

Fig - 12 (d)

Fig - 12 (e)

Fig - 12 (f)

Fig - 12 (g)

Fig.12: SHS to SHS Connection for the Inner & Outer Trusses

Fig.13: CHS Profile Cutting

Fig.14: Under Construction with temporary support's & staging

Fig.15: Column Base & Strut

Fig.16: Column Truss Connection

Fig - 17 (a)
Tekla View

Fig - 17 (b)
Actual View

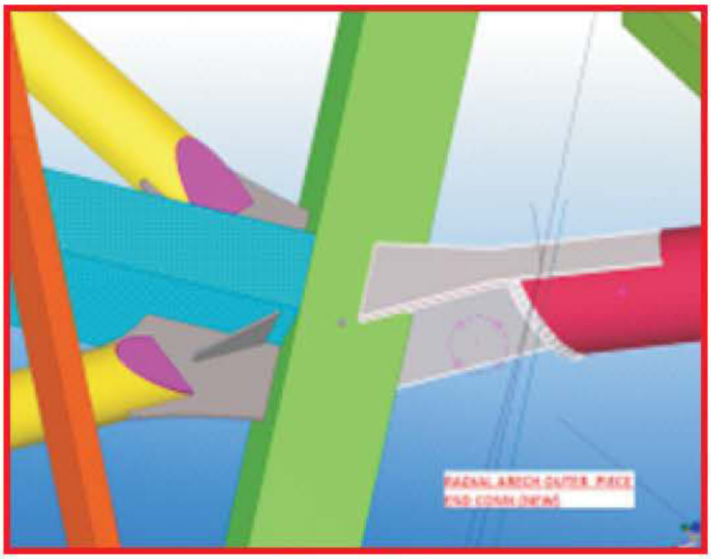

Fig - 17 (d)
Actual view

Fig - 17 (c)
Tekla View

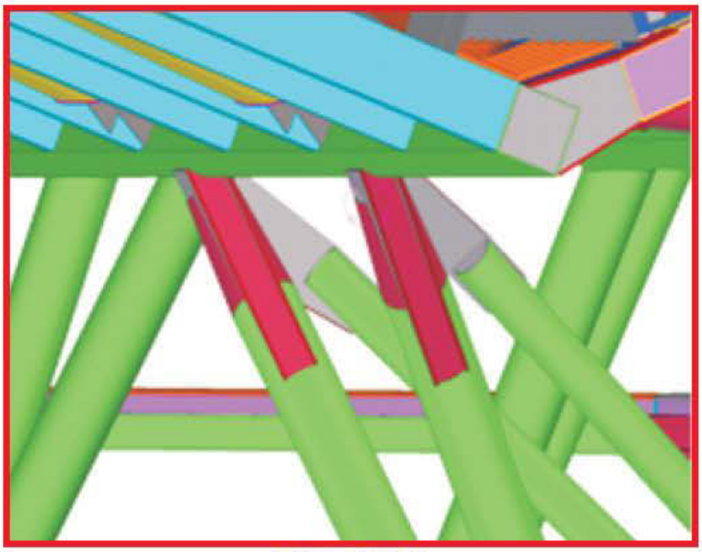

Fig - 17 (e)
Tekla View

Fig - 17 (f)
Actual View

Fig. 17: Connection Views

Fig.18 Under Construction with steel decking

Fig.19: Under Construction with steel decking on Roof partly erected

Fig. 20: Partly Completed Views

Fig. 21: Views from Top of Steel Decking - lower skin

Fig. 22: Views from Top of Roof showing the double skin in foreground - Steel Decking below, Insulation, clips (black color) and aluminium top skin laid in one piece end-to - end on curve

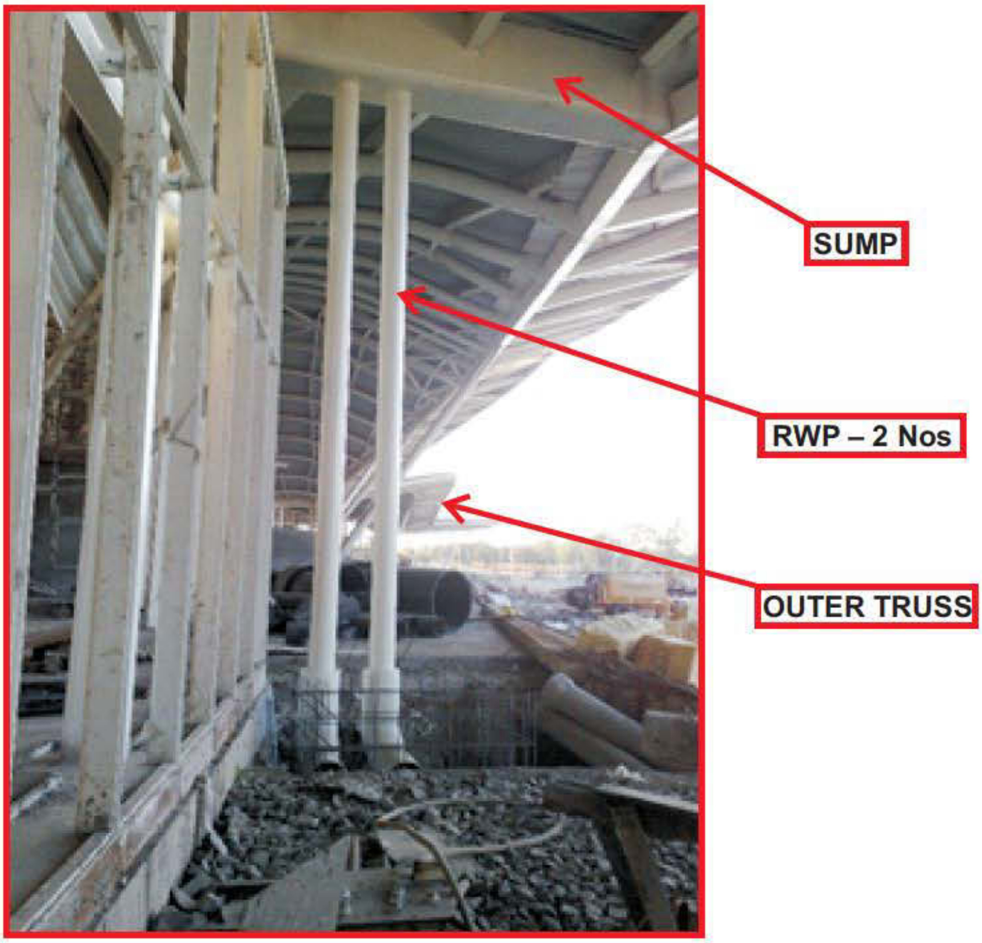

Fig. 23: View of Sump and RWP (2 Nos)

Fig. 24: Views of Pedestrian Footbridge between Exhibition Centre & Business Centre

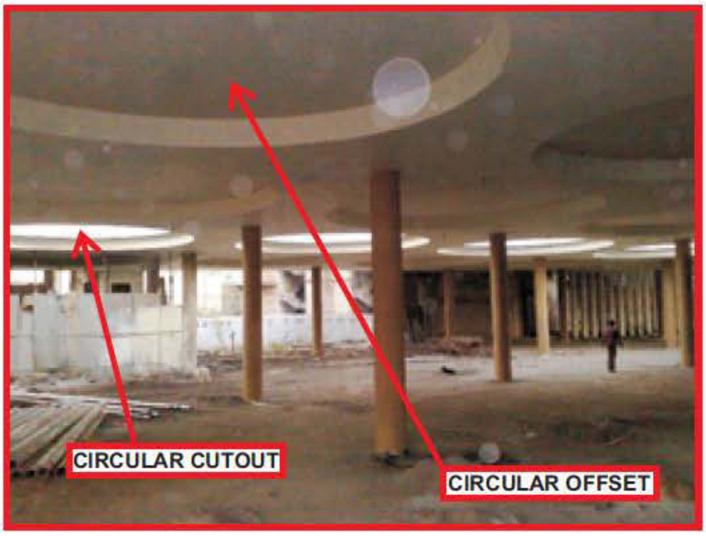

Fig. 25: Views of Public Plaza

Fig. 26: Views of Grand Stair (above) & Central Hall (below)

2. BUSINESS CENTRE :

The Business Centre comprise of a Business Centre which is entirely RCC framed Construction and an Auditorium structure of 585 seating capacity, wherein the Roof structure is in steelwork supporting RCC slab on decking. The two structures are joined by a foyer area that has steel roof at 17.5m level. (Fig. 1a & 1b, 27 ,28 & 38)

Auditorium Roof **–** The steel roof of dimension 38m x 42m comprise of RCC slab on decking at 19.5m level , which are supported on steel beams at 1.875mc/c spanning between WARREN Profile steel trusses (5 nos) at 9mc/c . The steel trusses are about 3.5m deep and span 28m on RCC Columns and two trusses cantilever further 10m beyond the Auditorium wall into the Foyer area to support the structural steel suspended framework of Glazing 15m high .The cantilever truss depth tapers from 3.5m on column c/l to 2m at the end and supports a stepped RCC slab on decking (Fig. 28,29,30, 32 & 34). Within the Auditorium , platforms are supported at bottom chord of Truss for supporting the suspended Light bars, Boarder bars for Stage performances, and further several catwalks are suspended between bottom of truss and false ceiling for Light bridge, Maintenance access , Light slots, etc, which were fabricated in modules and bolted to cleats/plates on the bottom chord of the trusses (Fig 30 & 37).

Foyer **–** The Foyer area (Fig 1b) between the Auditorium & Business Centre comprise of RCC slab on decking at 17m level from ground floor , supported on steel tapered beams @ 2.4m c/c spanning between steel lenticular truss on the inner end and Foyer columns on glazing end , and further cantilevers beyond glazing end that varies from 3m to 8m (Fig 28). The Steel Lenticular exposed Truss, 4.8m deep and 23m span , forms an architectural feature in the foyer and besides supporting the Foyer slab at +17m, also supports slab at +12.50m level below and terrace slab above at +23.5m level. The Lenticular Truss comprises Compression Arch of box section fabricated from plates and Tension Arch of Twin plates section, and loads are transferred to these 2 arches thru vertical members @ 2.8m c/c of box section or 2 flats (Fig. 28,30,33 & 35) . The columns on Glazing end are 17m high and are box section comprising steel I – beams + plates.

Foyer Suspended Glazing - The Suspended Glazing framework comprise of 200mm wide steel plate mullions suspended from end of cantilever Truss and tied by Transoms of T- shape c/s, for supporting the aluminium framework of the glazing. For providing adequate stability for wind loads, the framework is connected to building wall by inclined struts of pipe c/s (125Ø to 200Ø) to form a collage as visualised by the Architect. (Fig.27, 28,29 & 36).

The Entire Auditorium Roof & Structures along with Foyer Structure & Suspended Glazing was modelled on STAAD for analysis & design due to various loads – Gravity loads, Live Loads on Roof & Platforms, Service loads & Wind loads/ Seismic loads (Fig.31).

The entire structure with all connections was modelled on TEKLA Steel software due to the skewed geometry (Fig.28) and all shop drawings were generated from the model. The trusses were erected in one full 38m piece. The entire steelwork was of Grade E250 using Universal Beam/Column sections of JINDAL Steel and all hollow sections of TATA STEEL. Painting of all steelwork after shot blasting comprise of sprayed on epoxy primer (shop painted) and finish coat on site using sprayed on polyurethane finish for Internal steelwork within the structure and polysiloxane finish for External steelwork outside the structure. All touch-up of primer after field welding of connections was carried out by suitable compatible primer.

Fig. 27: Architectural Rendering-Business Centre & Auditorium

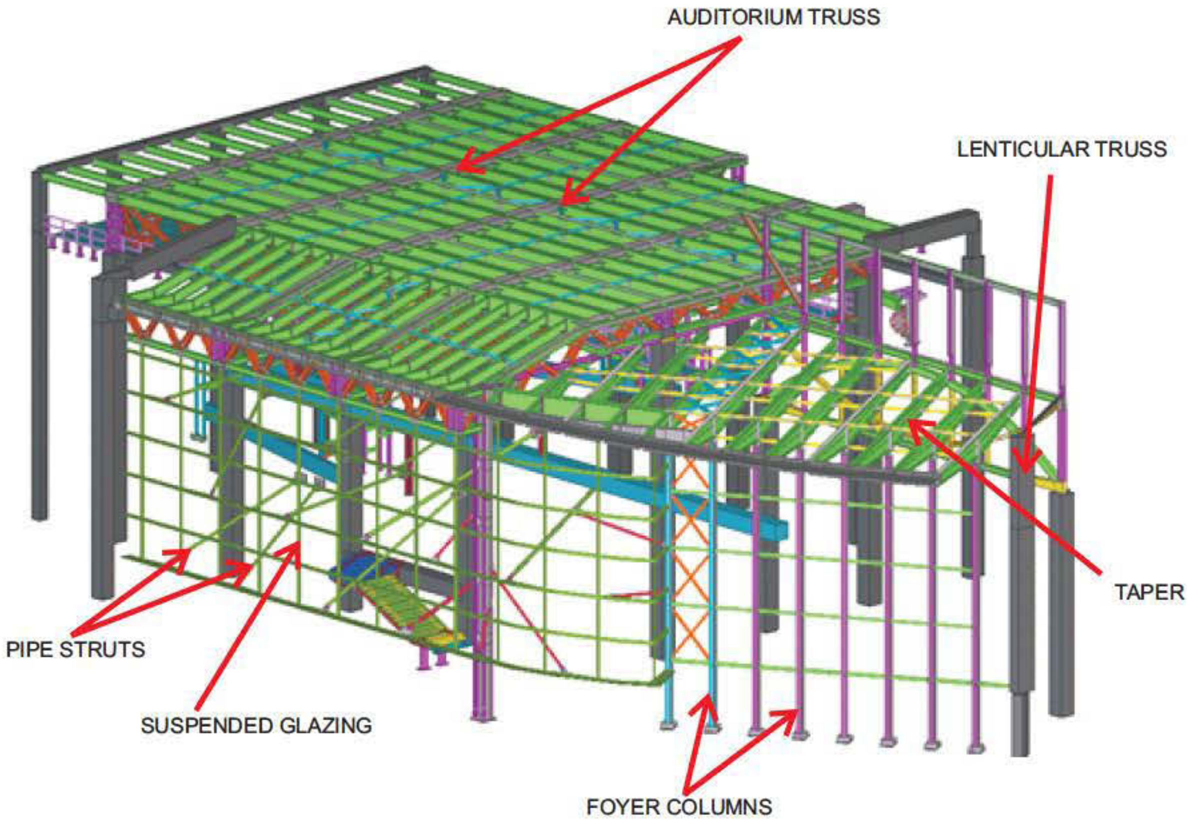

Fig. 28: Isometric View – TEKLA Model

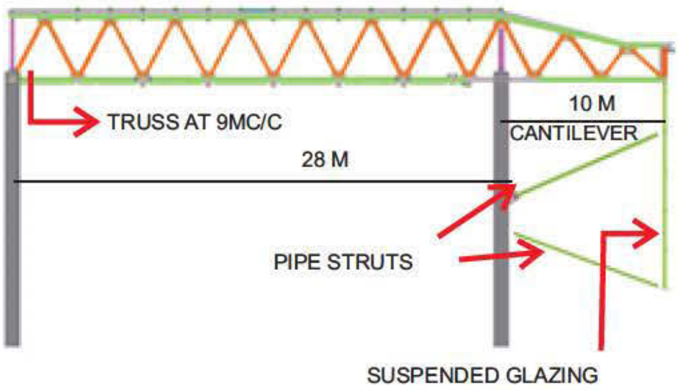

Fig.29: Cross Section-1 (from TEKLA model)

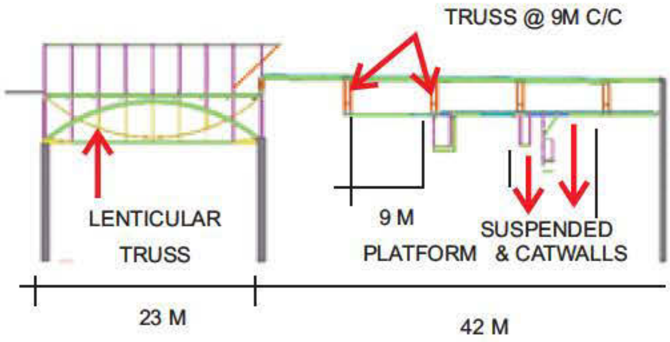

Fig.30: Cross Section-2 (from TEKLA model)

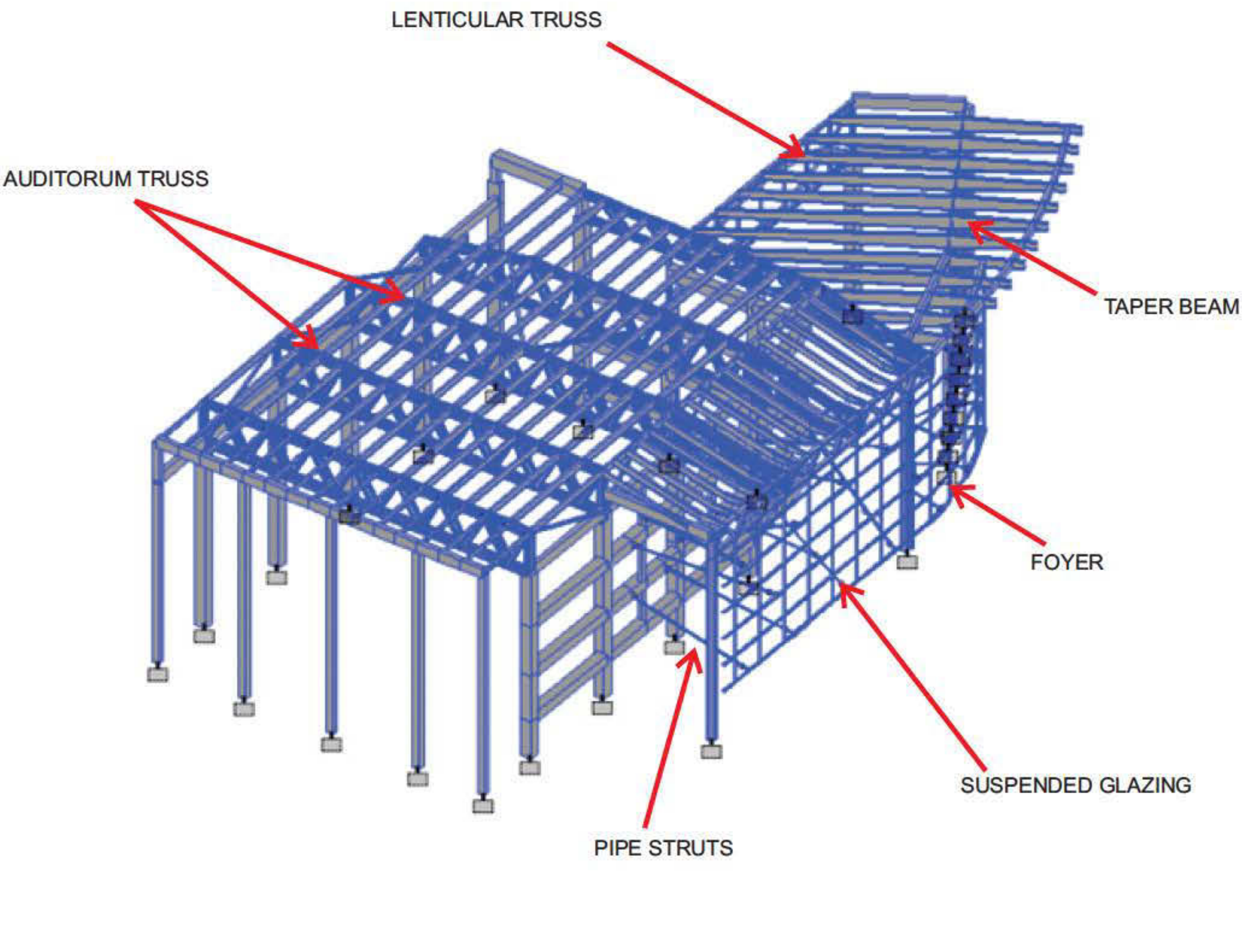

Fig. 31: STAAD Analysis model

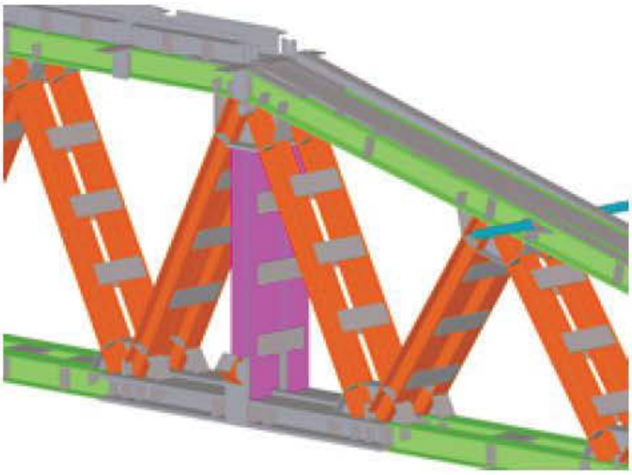

Fig.32: Auditorium Roof Truss
(from TEKLA model)

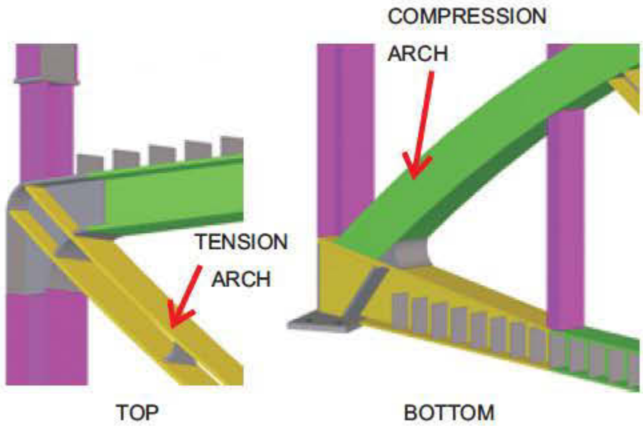

Fig.33: Lenticular Truss connection at top & bottom
(from TEKLA model)

Fig.34: Auditorium Roof Truss under construction

Fig - 35 (a)

Fig - 35 (b)

Fig - 35 (C)

Fig - 35 (D)

Fig.35: Lenticular Truss after erection

Fig. 36: Views of Foyer Suspended Glazing and bracings

Fig 37 – Suspended platforms from the underside of Auditorium trusses

Fig.38: Overall view of Business Centre under construction

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Architect : Ratan J Batliboi – Architects Private Limited, Mumbai
Structural Engineer: SPA Consultants Pvt Ltd, Mumbai
Service Consultant: Sheth Techno Consultants Pvt. Ltd, Ahmedabad
Civil & Steel Fabrication Contractor: IVRCL Infrastructures & Projects Ltd, Pune
TEKLA & Shop Drawing Consultant: inSTEEL ENGINEERS Pvt. Ltd., Navi Mumbai

STRUCTURAL ENGINEERING - AN ART OR SCIENCE ? PART 1

Dr. Subramanian Narayanan

Introduction

The profession of Structural Engineering is defined by The Structural Engineer, The Journal of the Institution of Structural Engineers, London, UK, as below [Collins (2001)]: 'Structural engineering is the art and science of designing and constructing structures with economy and elegance so that they can resist safely the forces to which they may be subjected.'

While the objectives of economy and safety are probably well understood and considered by all designers, the objective of obtaining elegance in structures is not well understood. Note that in modern structures, it is also important to consider other design criteria such as stability, serviceability, durability, sustainability, construction ability, and ductility [Subramanian (2013)].

Collins expressed that "While the public may believe that the design and checking for safety of major structures is a precise science requiring mere methodical calculation, the truth is rather different". Many researchers will agree with the definition of structural engineering given by E. H. Brown "The art of moulding materials we do not really understand into shapes we cannot really analyze, so as to withstand forces we cannot really assess, in such a way that the public does not really suspect." Freyssinet regretted that some engineers, rather than develop the structural art, intuition, and understanding that come only after immense effort, prefer to "shelter behind their mattress of equations, which they judged to be more effective the more complicated they were" [Collins(2001)]. Unlike olden days when primitive tools such as slide rules were used for calculations, we now use sophisticated computers and software which relieve designers from doing complicated calculations. However, elegant structures are a rarity and truly innovative and elegant structures are designed only by very few experienced designers. In this paper we will confine our attention to the aspect of elegance, i.e. the art of structural engineering. As art is difficult to explain than science, we will explain it through a few examples of elegant structures built during the last two millennia around the world. It has to be noted that many books have been written by Prof. D.P. Billington on this topic (1-4,7). In part 1 of the paper, early examples of elegant structures are covered and modern elegant structures are covered in part 2.

Early Elegant Structures

The earliest treatise on architecture called De Architectura was written by Marcus Vitruvius Pollio, who served as one of the engineers of the Roman emperor Julius Caesar. Vitruvius stated that buildings should exemplify "firmitas, utilitas, venustas"; that is, they should be safe, useful, and beautiful. He emphasized that even structures built for "utilitarian purposes" should satisfy these objectives. The beauty of Roman structures may be found great Roman bridges such as the Alcántara Bridge (also known as Puente Trajan at Alcantara) and Pont du Gard, which are stone arch bridges having semicircular arches with rise equal to one-half the clear span (see Fig.1). The inscription on the bridge contains the following information about its builder: "I, Caius Julius Lacer, famous for my art, leave a bridge to stand forever in the centuries of the world." Nineteen centuries later the bridge still carries traffic across the Tagus River!

Fig.1 Alcántara Bridge at Alcántara, Spain built between 104 and 106 AD by an order of the Roman Emperor Trajan

(Source: http://en.wikipedia.org/wiki/Alc%C3%A1ntara_Bridge)

Romans also built arch bridges for river crossings with gently sloping terrain. An elegant example of such a segmental arch bridge is at Cuidad Rodrigo, the arches for which rise less than one-third their spans. Another remarkable structure built by Romans around A.D. 120 by the architects of Hafrian is the Pantheon in Rome (Fig. 2). Constructed using lightweight aggregate concrete, the Pantheon is as tall as a 15-story building and consists of a hemispherical dome with an internal diameter of about 43.3 m. The interior coffering not only is decorative, but also reduced the weight of the roof, as did the elimination of the apex by means of the oculus.

Fig. 2 The interior of the Pantheon, painting by Giovanni Paolo Panini (source: http://en.wikipedia.org/wiki/Pantheon,_Rome)

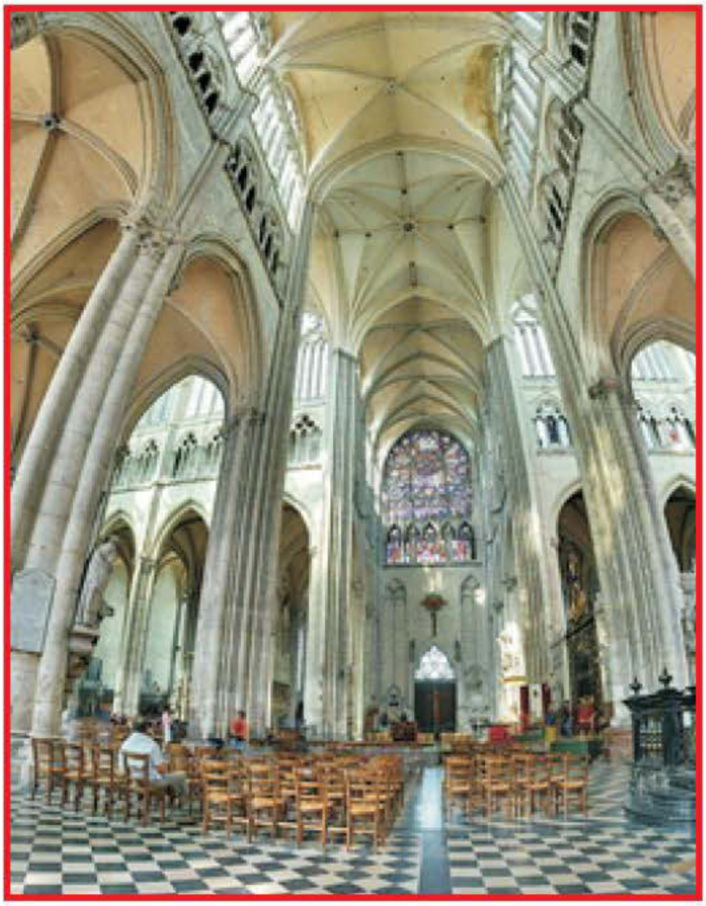

Fig. 3 Interior of Amiens Cathedral, France

Elegant Structures Built During the Medieval period (5th to the 15th century)

Several Gothic cathedrals in Europe, built between A.D. 1100 and 1450 stand testimony to the creativity and elegance of its creators. For example the Amiens Cathedral, France, constructed during this period, contains the largest medieval interior in Western Europe, supported by 126 pillars (see Fig. 3). Its stone-vaulted nave has an internal height of 42.30 m. The internal dimensions of these Gothic cathedrals were maximized in order to reach greater heights and to bring in more light through many stained glass windows that are provided in their thin walls.

Structures of the Renaissance Period

The Renaissance (meaning Rebirth) was a cultural movement that occurred during the 14th to the 17th century, beginning in Italy in the Late Middle Ages and later spreading to the rest of Europe. Around 1485, Leonardo da Vinci presented the famous drawing of a perfectly proportioned man which is based on the correlations of ideal human proportions with geometry described by the ancient Roman architect Vitruvius in Book III of his treatise De Architectura. As an engineer as well as an artist,Leonardo thought about how structures resisted loads, and also conducted experiments on the strength of columns, beams, wires, trusses, and arches.

During this period (year 1566), The oldest single arch stone bridge was built with a clear span of 28.7 m across the Neretva River at Mostar in Bosnia-Herzegovina by the Ottoman Empire's architect Cejvan Kethoda. It is was hailed as one of the boldest and most beautiful of all stone bridges (see Fig. 4). Its arch was only 770 mm thick, or 1/37th of the span, whereas as per Roman practice it would have required a thickness of about 1/20th span.

Another Italian, Galileo Galilei, was almost as remarkable as da Vinci. Like Leonardo, Galileo conducted experiments to understand how structures behave. He was the first to understand the behaviour of cantilever beam, though he wrongly assumed that the whole cross-section of the beam will be in tension (see Fig. 5). Unlike Leonardo, he published his findings in the form of books; in 1638, at the age of 74, while under house arrest (for opposing the Church's view that all heavenly bodies revolved around the Earth), Galileo published his most comprehensive text, Dialogues Concerning Two New Sciences [Collins (2001)]. He correctly predicted that the fracture moment of the rectangular beam is proportional to the width times the square of the depth, and that the fracture moment of a circular beam is proportional to the cube of the diameter, thus sowing the seeds for the engineering beam theory!

Fig. 4 Neretva River Bridge at Mostar
(source: http://en.wikipedia.org/wiki/Mostar#Architecture**)**

Fig. 5 Galileo's bending test,
from *Due Nove Scienze*, 1638

Robert Hooke (1635-1703) who discovered the famous Hooke's law of elasticity also drew a remarkable diagram showing that he clearly understood the principal hypothesis of engineering beam theory, i.e., "plane sections remain plane". Hooke designed personally at least 35 major structures, including the 62 m high Monument to the Great Fire, completed in 1677 and is considered as the tallest free standing stone column in the world. In many projects, including the St. Paul's Cathedral, in London, England, Hooke collaborated with the architect Sir Christopher Wren. (It is of interest to note that Hooke was not given sufficient credit for some of his discoveries as he became involved in bitter controversy with Newton).

Fig. 6 Monument to the Great Fire, and
St. Paul's Cathedral, London

(source: http://en.wikipedia.org/wiki/St_Paul's_Cathedral)

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- About Us
  - History
  - Formation
  - Aims & Objectives
  - Important Issues
  - Bye Laws
  - Management
  - Our Centers
    - Mumbai Local
    - Pune Center
    - Solapur Center
- News & Events
  - Future Events
  - Latest Happenings
  - Past Events
    - Seminar
    - Workshop
    - Lecture
- Membership
  - Join ISSE
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- Publications
  - Books
  - Quarterly Journals
  - Standard Certificate
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Month of Jan- Feb-Mar-12

Contents
1. Fraternity news
2. Report on ISSE 14th Foundation Day Celebration By H. S. Vadalkar
3. Wind Engineering For Design of Structures Fundamentals By K.Suresh Kumar
4. Structural Design of the ICICI Bank Regional Hub, Haderabad By Girish Dravid
5. Pipe Line Rolling Across Pile Bents for the Tata Power Co. Ltd., Trombay By A. B Karnik
6. Earthquake Resistant Design of Structure and Experimental Analysis of Scaled Model By Samir Dhuri

Month of Jan- Feb-Mar-12

Contents
1. Fraternity News
2. Effect of grade of steel on load capcity of Composite slabs By Pragnya Shah, Brijesh Pandya & Harismita Pathak
3. Design and Consturction of Wirewound Cicular Precast, Prestressed Concrete
Thanks By Sanjay Mehta

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