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Introduction
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1.1 An Overview

This dissertation is about structure in a specialised channel – as it is linked with architecture, and which, often in the art of building, goes unnoticed. Yet, most of the powerful examples of architecture from time immemorial have come about through extraordinary innovative accomplishments in structure.

In the development of human civilisation a stage had arrived when man emerged from cave dwellings into habitable man-made buildings and other structural formulations for better living. The process of evolution continued. Theoretical understanding, however, was slow and remained limited to practical skills.

This situation changed in the twentieth century with a quantum jump in the advancement of technology and with the advent of the computer. Total reliance on intuitive understanding, experience and historical precedents came to an end, and a significant emphasis began to be placed on research and scholarship as a basis of architectural practice. Whereas this progression was clearly visible in the professions of law, medicine and engineering, such evolution remained comparatively slow in the field of architecture. The call for such an expanded and deepened knowledge, particularly in this country, received limited support from most of the practising architects.

Architecture as a profession cannot be based entirely on intuition, experience and precedent. For purposes of growth it must also be based on knowledge carefully acquired through research. Whereas there is a broad range of performance needs, structure is one important area in which deeper knowledge is particularly required.

From the temples at Karnak, the Hindu temples of India, from the Giza pyramids to the Collosseum, the Eiffel Tower, and on to the more sophisticated structures of the past few decades—skyscrapers, bridges, television towers, domes and docks etc., — technology and concepts have combined to produce masterpieces of artistry and environmental order. There is no doubt that, behind every striking building, there exists a supporting framework of ingenuity answering to practical and functional considerations.

One of the constants in architectural debates has been whether form really follows function or whether it makes the function possible. Though convincing arguments on both sides may flow back and forth, traditionally, architecture was created only through an absolute understanding of structure. The total vision of architects and structural engineers can become reality only, if a conscious complementing of knowledge and skills of both takes place. For it is not only the flashes of brilliance in structural or architectural design or material science that count, but a climate of enlightenment and co-operation that underwrites these successes. The great master of structural innovation, Mies Van der Rohe speaking of the relation of architecture to structural engineering, that they must “grow together”
that some day one can be the expression of the other, underscored the basis of a new form of building design: "effective architecture".

To generate and promote "effective architecture", architectural research must freely borrow from a range of other fields. This includes a creative collaboration of architects and structural engineers as an important requirement. The interactive nature of architectural projects makes a comprehensive approach necessary, to deal with the space-form implications of a broad range of interacting performance needs and fulfilling these activity-generated needs in a collectively optimum manner. This would require both participants (the architect and the structural engineer) to creatively collaborate at the schematic stage—not one first and the other later, with sufficient regard about technological and structural issues involved for the overall picture to avoid a conceptual zag.

Space and mass are the primary determinants of architectural form. Quality of architecture is largely determined by the nature and quality of space it embodies and the form through which the space-volumes are realized. Architectural form is an expression of the philosophical interaction of various sets of pressures peculiar to a particular set standards of excellence for architectural statements.

Structure is the means through which the architect realises the form. No organism, whether animate or inanimate, can exist without structure. Although structure alone does not make architecture, it makes architecture possible. Structure is neither an end nor a beginning; but a means to an end, and that end is to create appropriate psychological environment. Architecture is not structure per se. It is based on structural elements and goes beyond structural achievements. Although there are many elements which make a building, none is so vital to the existence of the building as structure is. Any valid architectural statement cannot ignore the importance of structure, and it is vital to develop the structure to the same extent as function and form.

Architects are also becoming increasingly aware of the aesthetic potential of structures. The purpose of structure is not merely to make the building stand, but also to re-inforce the spatial intention and be an active element of architectural expression.

The Industrial Revolution brought about an unprecedented and rapid change in terms of physical pressure for space, the psychological attitude towards space, and the structural options which makes possible the realisation of the spatial intentions in concrete form. Science and technology enable us today as never before to build any form. The vocabulary of form has been enlarged beyond comprehension. Architecture has been liberated from restrictions of space and form, Structural forms have become an absolute and undisputable standards of architecture.

The most significant impact of new Structural Systems was in terms of freeing the wall from load and giving a free un-interrupted space. Space thereby
becomes flexible and fluid medium instead of being rigid and compartmentalised in character, to be moulded at will by the architect—a total change in the character of space. Architecture becomes lighter and less earthbound—a characteristic which changes the architectural imagery. The unlimited structural options have enriched architectural thinking.

Thus, the system-approach has become acceptable in today's architectural thinking. This concept partly owes its existence to the computer which enabled man to streamline his ideas in understanding and giving solutions to his conceptual thinking. The computer today has become his greatest source of encouragement to tackle new unexplored ideas and tread unchartered paths and deal with realities which he could not dare to face earlier. So computers and systems in architectural engineering go hand in hand. This combination has helped considerably in scaling new heights in re-orientation in concepts and ideas in building design. The computer-cum-systems approach made it possible for a departure from the outmoded conventional approach in architectural thinking.

One of the principal sub-systems in building design is the structural scheme which forms the backbone of the entire design. The evolution of structural systems for buildings is an interesting study in itself. We have gone a long way from the 19th century column-over-column, slab and wall system.

Classical methods of frame analysis such as slope-deflection method, moment-distribution method and their numerous variants have been largely superseded by the more refined methods using matrix formulations suitable for computer. The Finite Element Method is (one such widely used latest method) for the computer analysis of plane or space frames, in multi-storeyed buildings, at present.

Structure is the *sine qua non* of all that has physical existence. In other words nothing can exist physically, without structure being there in the first place.*

As this study pertains to structure, primarily, we have to create a context for this exercise. In my view, Chandigarh is the best known context for this work. As everyone knows—Chandigarh has been hailed as one of the greatest experiments in the modern world in terms of planning, urban design, construction techniques, new materials; above all, new structures.

Although Chandigarh is modern in many ways, yet there are few modern structures in the City. The best known structures here—which are now acknowledged as masterpieces of modern architecture—are: The Secretariat, the Assembly Hall and the High Court. But in my view, even these three structures are very primitive in conception.

*Research Interview, Dr S.S. Bhatti* [From here to the end of the overview, the text is entirely based on Dr Bhatti's views on the field of structures in general and the subject of this thesis in particular.]
For example, the Cupola of Assembly supposed to be a Shell Structure— but its average thickness is more than 15 cm, which hardly qualifies it is a shell structure. In the same way, the parasol roof of the High Court is not a shell structure, although it has been conceived as one. If you go to the rooftop, you can see a very intricate network of hangers from which the shell that you see underneath, as the ceiling has been suspended. This, in my view is also not a shell structure at all. A shell structure primarily means two things: it has a curve and is thin, which together mean: the most optimum use of materials. In these two examples, at least, I have not been able to figure out, whether (these two) required parameters have been met.

Elsewhere also in the city, where modern structure in terms of RCC Frames have been tried, they are not structures, in the scientific sense of the word, because the basis on which they are worked out— was derived from Le Corbusier’s Le Modulor— a scale of dimensions— which he developed over 25 years of research. For instance, the City Centre 17”-3” (span) is a dimension derived from this Le Modulor (Scale) of Le Corbusier. This dimension has nothing to do with the space that will be necessary for various functions these structures are expected to fulfil such as shopping, offices— and the flexibility with which the space is required to be used in modern times,. At best, this dimension is an aesthetic dimension and not a utility dimension. For instance, if I want to use the same structure for underground parking, I will not be able to park two cars within this space, for which the internationally accepted dimension is 6.5 meters. Since Le Corbusier was an acknowledged master architect, he did several things in the city, which were not questioned. At any rate, our architects and engineers, at that point of time, were not qualified or experienced enough to question the validity of what was being done in the city. And now is the time to explore what went wrong and how can we correct that situation for future use— rather than blindly follow a tradition, which has little rational basis.

I personally feel that the basic dimension of a structure, in terms of the opening statement, should be based on utility first and foremost i.e. we must identify the functions the space will perform or is expected to perform for which a structure will be necessary to be built. Therefore, as one of the studies to support the research project, would be to identify and classify different structures in the city which have been built for performing different functions, such as residential, commercial’, office or such other, because from that analysis we will determine whether the structure put up for these functions are appropriate in terms of multiple use of space, which they create, as well as in terms of flexibility, which is expected of them.

An this point, it is pertinent to recall what Mies van der Rohe termed: The Universal Space. To my information, he was the only architect of the modern world, who actually could appreciate that flexibility is an essential feature of any modern structure whatsoever. The reason being that nobody however ingenious can foresee the changes which so quickly come about in the modern world. And since you must have structures which adapt themselves to the changing socio-economic needs of the human community, Mies thought of structures which could provide Universal Space in terms of column-free space. With
Universal Space, one could design the interiors in any manner whatsoever by virtue of the flexibility it provides for fulfilling varied requirements of utility.

The main objective of the present study commence from this concept of Universal Space. If the study is to become relevant and useful to the contemporary situation and the coming times, the argument for such a study would be that the system we are going to develop will make the creation of Universal Space for varied functions possible in an economical and efficient way. It has got to fulfil these two basic parameters, besides flexibility, in order to become relevant and useful in the modern context.

The main thrust of the study would be identification of special(ised) Functions for different human activities, the Structures already tried in Chandigarh for them, and the drawbacks they suffer from, so that the solutions that we offer as alternatives to the existing ones can be sold on the basis of the stated parameters. This System would be more flexible, more efficient, and more economical to adapt and build. It should be obvious that we have to define these parameters for the purpose of this study.

The term Economy in this context means: wise spending in terms of optimal use of available resources i.e. men, methods, materials, and machines. In my view, optimum is minimum, put to a maximum use. It is to be hoped that this definition makes the notion of economy an inalienable parameter, rather than something relevant only to a given situation. Just because one can afford to waste is not a rational way of building. On the contrary, even when you can afford to waste, your system should not let you. Only then I would think that the parameter of Economy is fulfilled, rationally.

In the same vein, Efficiency would be how quickly you can build the structure, and how easy it is to maintain it.

Further, Flexibility, as noted earlier, would mean the same structure can be adapted to varying human activities, without straining the basic conception which the structure is built.

As an extension of this idea, it would be necessary to identify case studies, which along this stream of thought, and develop new concepts on the same lines in the pursuit of fulfilling the stated parameters of Economy, Efficiency, and Flexibility.

In the end, I suggest that a diagrammatic or a graphic representation of this synopsis should be made for guidance so that the thrust of the study is not lost, and the objectives which we have in mind are clearly pursued and fulfilled.
1.2 Stimulus for Research

I am tempted to recall the year 1989, in which I was working on field projects in Chandigarh and Shimla (Mashobra), when I came across during the plan development and its actual constructions/working stage— the need was felt time and again to devise means/techniques for spanning column-free spaces, in the flat working floors in R.C.C. structures for normal and medium spans. At that time, out of sheer intuition, in addition to professional and education background— I happened to attempt a technique of stiffening grid-intersection(s) at the specific locations (to avoid columns).

As luck would have it, after more than a month, this maiden attempt started showing signs of more and more promise(s).

Then I started searching for relevant literatures to articulate my ideas of grid-stiffened structures. It continued like this for many months and years.

In the year 1994-95, I got a chance to assist one of M.E. Structures student in an area of experimental work. During 9-12 months association with student and engaging with him particularly, I started getting more and more feed back, while working on Computer-Parametric variations. It started showing more and more satisfactory signs of structural responses on the one hand and on the other hand, it also started indicating that a lot more needs to be done in this emerging area. I continued to search, discuss with professionals, peers and started looking for the directions and guidance. Eventually, in 1995, I got myself registered for PhD in the integrated disciplines of architecture and structural engineering.
1.3 Hypothesis

For the present study, the following hypothesis has been attempted:

The structure system, in the form of framed configurations (with 2-D and 3-D concept in RCC and Steel)—folded plates, vaults, and shells—works best in common usage for roofing requirements only. It does not create large-span, column-free spaces beyond 12-15 meters (40-50 feet) to permit flexibility to accommodate rapidly-changing requirements which characterise the modern era.

So to overcome the present limitations, an unconventional technique has been introduced in the structure form, which is being developed as follows: In the existing grid system (Figure 1.1 on p. 11) additional grouping of 2 members (Nodal Members) around each additional intersection point (Junction Point/Node Point*) at a certain spacing and at a certain inclination in the form of a diamond shape (in the present specific case) has been done. The new configuration has been given the nomenclature: Grid-Nodal-Matrix-Based Structural System (Figure 1.2 on p. 12), which will be used for future referencing in this study.

The primary purpose of developing this framework is to decrease the value of deflection and stress-resultants at strategic locations of the existing grid-system, by providing additional stiffness—because stiffness plays fundamental role, in the mechanism of all structure systems, for all kinds of loading conditions, and for all spans.

In other words, this all-important aim could be achieved by introducing the advantages of Vector-Active Structural System** in the Bulk-Active Structure System*** (which forms the groundwork for the present study) when the latter is transformed into Grid-Nodal-Matrix-Based Structural System with the implantation of certain Nodal Members at strategic points, as noted above.

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* Junction Point/Node Point: A junction or node is a coordinate location in space where degrees of freedom (displacements, rotations, etc.) and actions (forces, moments, etc.) of the engineering system are deemed to exist.

Each node possesses certain degrees of freedom (DOFs) which characterise the response of the field. For a 3-D structural system, the full set of DOFs includes three translations and three rotations.

** Vector-Active System: Short solid, straight-line elements/members used as structural members/components carrying/transmitting forces/stresses in the direction of their length. The forces/stresses transmitted may be tensile and/or compressive as the situation demands.

*** Bulk-Active System: It consists of the combined action of compressive and tensile stresses with/ across the beam section in conjunction with shear stresses, due to bending deflection in the members carrying load. The distribution of its bulk, in relation to the natural axis of members, plays a decisive role in designing/governing/generating internal strength as required.
Figure 1.1: Conceptual Framing Pattern: Initial Stage Formulations

Legend

- Edge Member (em): 4, 5, 13, 21, 18, 17, 19, 11
- Main Member (mm): 30, 31, 32, 33

Y=Vertical Dimension along Y-Y axis
X=Horizontal Dimension along X-X axis
Z=Horizontal Dimension along Z-Z axis
Figure 1.2: Conceptual framing pattern: Final Stage Formulations
The following classification of spans has been employed in this study:

- **Upto 7.02 Metres**: Normal Spans
- **Upto 12.27 Metres**: Medium Spans
- **Upto 22.27 Metres**: Medium-Large Spans
- **Upto 33.27 Metres**: Large Spans
- **Beyond 33.27 Metres**: Extra-Large Spans

For improving the effectiveness of the present system (conceptualised) a slope (arched-effect) may be introduced at places in the main stiffening beam member/line elements.

For large spans, additional Grid-Nodal-Matrix-Based systems are implanted and investigated for mobilising additional Grid-Nodal-Matrix-Based effects at a certain spacing— for which a parametrical study may be undertaken separately, to document reference work in the form of tables and graphic charts.

An attempt is made to identify scientific laws for applications in futuristic structures, and to explore their influence on corresponding architectural forms.

Simple analytical/geometric models are generated and an exhaustive study is undertaken on computer system for different loading(s) on similar system to investigate its effects with the help of working on STAAD-III (20.1 and 22.00w versions) a ready-made software package for analysing, and for checking specific/simulated models on ANSYS (5.3) software. And results are tabulated and compared for drawing conclusions.

Testing work or experimental work is additionally conducted to study the Grid-Nodal-Matrix-Based effects, and the results so tabulated are compared with simulated models on computers for checking the computer results vis-à-vis actual-study-model loading results.

### 1.3.1 Project Profile

1. **Structural System**: Column-and-Beam Systems (Trabeated System).
2. System is analysed and studied after implanting Grid-Nodal stiffeners members (as above).
3. Experimental work has been carried out on a simulated scale model. The deflection and strain readings are taken with the help of network of dial gauges and strain gauges on model at critical locations.
4. Stress-resultant values by using standard elastic relations have been worked out.
5. Tabulation and comparison of the computer and experimental results has been done.
6. Feasibility study of the proposed system is tabulated vis-à-vis conventional systems to present the results at a glance.
1.4 Objectives of Research

(1) To study and (learn how to) apply available structural analysis/design software packages for developing new structural systems or modelled geometry.

(2) To work out innovative structural systems in the pursuit of advancing applied knowledge and to develop further as a pathfinder/seeker to face uphill challenges. This is to be developed on computers with available structural analysis/design packages available.

(3) To develop a library/ready-reckoner-type handbook of newly-created structural systems with tested results in order to make the systems applicability to innovative architectural forms easy and felicitous.

1.5 Scope of Work

The scope of this research exercise is restricted to the computer-aided study of Shape Evolution of Grid-Nodal-Matrix-Based System and the formulations (as a unit) thereof for large span, square-shaped plan in RCC structures with an eye on Futuristic Architectural trends.
1.6 Research Methodology

Research work on the hypothesis of this thesis has been carried out in a process using the methods and techniques as noted below:-

(1) The bulk of base materials sifted from technical books, reports, news bulletins, articles, reviews etc. has been used in the documentation of this work.

(2) Basic Structural System adopted: Column-and-Beam System (Trabeated system).

(3) Mix used: Minimum structural strength mixed (M-150) has been adopted for working out elastic data/parameters used in analysing and design of members, and elements.

(4) Planning Principals or Design Criteria evolved by Systems Analysis and studies have been carried out for both cases: without and with Grid-Nodal-Matrix-Based system implantations, with specific reference to deflection and stress resultant responses.

(5) Investigation has been carried out by changing Grid-Nodal shapes and sizes (Shape Evolution Study) for studying optimum values of stress resultants vis-à-vis pattern of development, under pivotal context study emphasised.

(6) Experimental work has been done on simulated Grid-Nodal-Matrix-Based scale-model with various point loading value(s) at critical location. The deflection and strain readings responses have been measured with the help of network of dial gauges and strain gauges used at selected locations on model system.

(7) Stress resultants values have been worked out by using standard elastic relations.

(8) Tabulation and comparison of computer and experimental results have been done.

(9) Drawing inferences and delineating logical guidelines/design principles evolved vis-à-vis new proposed system being adopted, while studying as a context material (resource base). These principles so evolved, are to be used as the bases for conclusions work to be carried out further as reference in teaching, research and field practice.
1.7 Presentation of Research Material

(1) Chapter 1 outlines an overview, background attempt made before present work undertaken, hypothesis (framework— envisaged, planned and articulated). And also, it sets out objectives of research, scope of present work, methodology adopted for research, and presentation of thesis work— as an reflection at a glance.

(2) Chapter 2 deals with literature referred and selected from the masters’ contributions in a research for widening the conceptual base in terms of patterns of development and exploration of ideas.

(a) Also, literature referred for related areas like structural Grid-Actions generation study, and to handle computer system, with Finite Element Literature, and its applications— for working on STAAD-III (Versions 20.1 and 22.0W), and ANSYS (5.3) is overviewed.

(b) Further, finite element methods are discussed with particular reference to STAAD-III (Versions 20.1 and 22.0W) and ANSYS (5.3)— readymade packages available from market.

(3) In Chapter 3, both these packages have been selectively used in the analysis of models/structure systems and for checking results, and response-patterns by studying different discretised models.

(a) And capability of coarsed-mesh (4 elements) case is discussed to give satisfactory convergence results supported with specific examples, to be used as basis for further research work in subsequent chapters.

(b) Scaled analytical models for different Spans have been shown to be adequate for representing the proposed structural systems behaviour patterns, starting from particular cases from which general trends are deduced. Results of analytical models are compared with those from experimental results.

(4) Chapter 4 is devoted primarily to the corroborate of shape evolution study, subjected to different loadings values in the form of pressure loadings used for studying behaviour patterns on a cast RCC model.

(5) Chapter 5 deals with the application of Grid-Nodal concept evolved earlier in Chapter 1. And results are tested in previous Chapters 3 and 4. And are again formulated in the form of extended-study-patterns, when scale is magnified further to develop its suggested patterns, in this chapter.

(6) Chapter 6: Various inferences drawn in previous chapters are consolidated here, and conclusions are worked out, and the extension of scope of present work is suggested in the form of strategy for future undertakings.

(7) For attempting self-contained documentation work, following references have also been appended towards end of main text material, which are as follows:-
(a) In the Bibliography, selected references used in this study are listed out for further study and verifications.

(b) Further, in order to develop self-contained documentation— supporting material supplement (Appendix) has been added towards the end of the dissertation to lend support to the intent and content of this research-based creative work.