# "MULTIPLICATION FACTORS ANALYSIS FOR CURVED RCC BOX BRIDGES:
# “A 3-D FEM APPROACH"


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## ABSTRACT

This paper explores the structural behaviors of horizontally curved RCC box bridges, encompassing bending, shear, axial, and torsional effects. It employs a 3-D Finite Element Method (FEM) using SAP software to analyze these behaviors comprehensively. FEM models are developed for various span lengths while maintaining consistent material properties. The degree of curvature ranges from 0° to 90°, and different load conditions and combinations are applied to assess the bridge's response.

The study aims to derive multiplication factors for essential parameters such as bending moment (BM), shear force (SF), axial force (AF), and torsional moment (TM) concerning straight bridges. These factors facilitate the translation of parameters from a straight bridge to a curved one, simplifying the analysis and preliminary design process of curved bridge sections.

## 1.0 INTRODUCTION

Horizontally curved bridges indeed offer innovative solutions to complex infrastructure challenges, particularly in situations where traditional straight bridges face geometric constraints or where site limitations are pronounced, such as at interchanges or river crossings. The curvature of these bridges allows for the alignment to adapt to the specific conditions of the site, enabling engineers to navigate around obstacles or conform to the natural landscape.

One of the key advantages of horizontally curved bridges is their ability to efficiently utilize limited space while providing structural integrity. By incorporating a cellular cross-section, these bridges can effectively distribute and manage high torsional moments, which are common in curved structures due to the asymmetric loading conditions. This design approach not only enhances the bridge's overall strength but also ensures economical construction and maintenance, as it optimizes material usage without compromising on structural performance.

However, despite their practical advantages, horizontally curved bridges have historically received less attention in terms of research and documentation compared to their straight counterparts. This relative scarcity of literature may be attributed to several factors:

1. **Specialized Expertise:** Designing and analyzing horizontally curved bridges require specialized knowledge and expertise in structural engineering, particularly in dealing with complex geometries and dynamic loading conditions. Consequently, fewer engineers may have the requisite skills to undertake such projects, leading to a lack of research in this area.

2. **Limited Precedents:** The relatively fewer instances of horizontally curved bridges compared to straight bridges mean that there are fewer real-world examples to draw upon for research purposes. This scarcity of precedents may deter researchers from exploring this topic in depth.

3. **Focus on Straight Bridges:** The majority of bridge-related research historically focused on straight bridges, which are more common and represent the conventional approach to bridge design. As a result, horizontally curved bridges may have been overlooked in academic and professional circles.

Despite these challenges, there is growing recognition of the importance and potential of horizontally curved bridges, especially in addressing modern infrastructure needs. Advances in computational tools, such as finite element analysis and computer-aided design software, have made it easier to model and simulate the behavior of curved structures, thereby facilitating research and innovation in this field.

Efforts to document and study horizontally curved bridges should be encouraged to further enhance our understanding of their design principles, structural behavior, and performance characteristics. By disseminating knowledge and sharing best practices, engineers can leverage the unique advantages of curved bridges to overcome spatial constraints and create resilient infrastructure solutions for the future.

In the current specifications outlined by the Indian Roads Congress (IRC), there is a notable absence of specific guidelines tailored for curved bridges, aside from the consideration of torsion moment. To accurately calculate torsional moments in curved bridges, a refined analysis is necessary. While the Finite Element Method (FEM) offers a comprehensive approach to analyzing such complex problems, its utilization presents challenges due to its inherent complexity. Consequently, bridge designers require simplified solutions to address these complexities.

In their paper, Ali R. Khaloo and M. Kafimosavi propose the use of a multiplication factor (M.F) to address this issue. This factor allows designers to determine the desired action in a curved bridge by multiplying it with the corresponding action of a straight bridge. Their study focuses on enhancing the flexural design of horizontally curved prestressed bridges. Through three-dimensional and refined finite element modeling and analysis, they investigate the flexural behavior of these bridges. Their findings reveal significant differences in stress distribution compared to straight bridges, with certain locations experiencing notably high stress levels.

The literature presents a dearth of knowledge regarding the flexural behavior of curved bridges, both in standard specifications and research papers. Consequently, engineers often resort to analyzing curved bridges using methodologies developed for straight bridges, particularly for spans with minor curvature. To address this gap, the authors compare analytical results of straight and curved bridges, providing charts and tables for various parameters such as shear, bending, torsion, and axial force in curved bridges. This approach aids in the preliminary design of horizontally curved bridges by leveraging straight bridge analysis with multiplication factors, considering factors such as the degree of curvature and span length.

To address the need for realistic analysis, a parametric study of curved bridges is conducted. Using three-dimensional finite element analysis software, SAP2000, the study investigates various behaviors including bending, shear, axial, and torsional effects in horizontally curved RCC box bridges. Forty models are developed for different span lengths (15m, 20m, 25m, and 30m) while maintaining consistent material properties. These models vary the degree of curvature from 0° to 90° at 10° intervals under different load conditions and combinations. The paper presents charts and tables detailing various parameters of curved bridges, providing valuable insights for bridge designers and engineers.

## 2.0 FINITE ELEMENT METHOD

The primary advantage of the Finite Element Method (FEM) lies in its broad applicability to a variety of engineering problems. Unlike other analytical techniques, FEM offers a high degree of generality, allowing for the approximation of virtually any continuum with complex boundary and loading conditions. This versatility enables engineers to expect accurate analyses across a wide range of scenarios.

Over the past two decades, FEM has emerged as a popular technique for solving complex engineering problems computationally. The method involves creating a mathematical model by representing a structure as an assembly of discrete two- or three-dimensional elements interconnected at nodal points, each possessing a specific number of degrees of freedom.

In the context of bridge analysis, the entire structure, such as a box girder, is divided into small elements. The stiffness of the structure is then determined by assembling the membrane and plate bending stiffness of each individual element. This approach allows FEM to handle all types of structures effectively.

However, the application of FEM to bridge problems requires a comprehensive understanding of advanced structural mechanics and numerical techniques, which may pose challenges for design engineers who may not have expertise in these areas. Nonetheless, FEM remains the go-to method for addressing complex engineering problems due to its versatility, generality, and computational power.

## 3.0 SAP- 2000 SOFTWARE MODELING \

The SAP-2000 software, developed by Computer and Engineering Software and Consulting, stands out as a highly integral, productive, and practical structural program widely utilized in the industry today. Renowned for its three-dimensional interface and utilization of the finite element method for analysis, SAP-2000 serves as a standalone program for the analysis and design of structures. Its robust user interface offers numerous tools that facilitate the swift and precise construction of models, complemented by sophisticated analytical techniques capable of handling even the most intricate projects.

One notable feature of SAP-2000 is its Bridge Wizard section, designed to streamline the model creation process. This feature comprises 12 steps aimed at simplifying and expediting the model-building process for bridges. The steps include:

1) Layout Lines: Layout lines serve as reference points for defining the vertical and horizontal layout of bridge objects and lanes. These lines, specified in terms of stations, bearings, and grades, can be straight, bent, or curved in both the horizontal and vertical planes. Various options are available for horizontal and vertical curves, with the Right Curve line being selected for this work.

2) Deck Sections: SAP-2000 offers a range of parametric bridge deck sections to choose from when defining a bridge. For this work, the Concrete Box Girder External Girders Sloped option has been selected. This option provides flexibility in designing bridge deck configurations to suit specific project requirements.

Overall, SAP-2000's Bridge Wizard section simplifies the process of creating bridge models by providing intuitive tools and options tailored to bridge design needs, thereby enhancing efficiency and accuracy in structural analysis and design tasks.

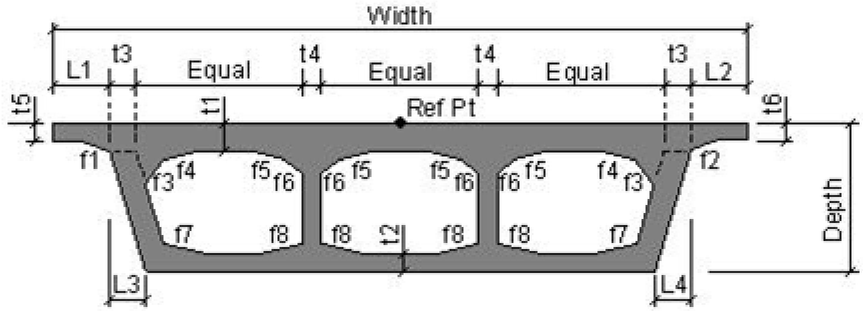


**Figure 1. Cross Section for Box Girder**

3) Abutment Definitions: Abutment definitions specify the support conditions at the ends of the bridge. These conditions can be customized, allowing each of the six degrees of freedom at the abutment to be designated as fixed, free, or partially restrained with a specified spring constant.

4) Bent Definitions: Bent definitions detail the geometry and section properties of the bent cap beam and the bent columns. Additionally, they specify the base support condition of the bent columns.

5) Diaphragm Definitions: Diaphragm definitions pertain to the properties of vertical diaphragms spanning transversely across the bridge. Solid concrete diaphragm properties are applicable only to concrete bridge sections. In all models, the end diaphragm thickness remains consistent at 0.4 m to mitigate local effects and ensure uniform distribution of large support reactions.

6) Hinge Definitions: Hinge definitions specify the properties of hinges, such as expansion joints, and restrainers.

7) Parametric Variations: Parametric variations allow for adjustments in the deck section along the length of the bridge. Parameters such as bridge depth, thickness of girders, and slabs can be varied. These variations can be linear, parabolic, or circular, and multiple parameters can be adjusted simultaneously with unique variations.

8) Bridge Object: The bridge object serves as the core of the bridge modeler. It encompasses several key aspects: (a) Definition of bridge spans (b) Assignment of deck section properties to each span (c) Assignment of parametric deck section variations to each span (d) Assignment of abutment properties and skews (e) Assignment of bent properties and skews (f) Specification of hinge locations, properties, and skews (g) Assignment of super elevations (h) Definition of prestressed tendons.

9) Update Linked Model: The "Update Linked Model" command in SAP2000 creates the object-based model from the Bridge Objects definition. This functionality enables the creation of spine models, area object models (Shell Element), and solid object models of the bridge when the linked model is updated. The Bridge Objects menu within the SAP2000 software facilitates this process, as depicted in Figure 2.

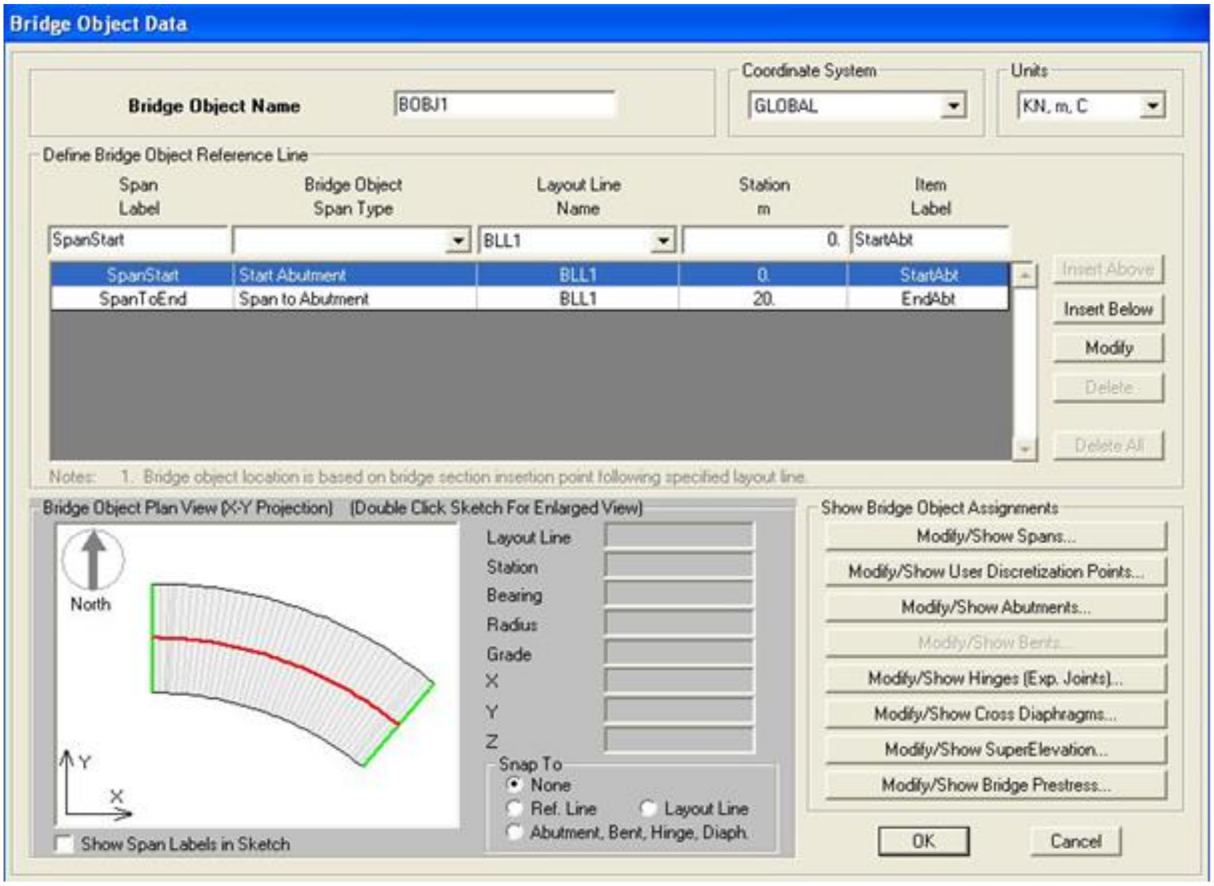


**Figure 2: SAP2000 software Bridge Object menu**

10) Lanes: Lanes must be defined for the analysis of the bridge concerning moving vehicle live loads. These lanes can be defined with reference to layout lines or existing frame objects. A single lane can be referenced to one or more layout lines or frame objects, and width can be assigned if desired. Lanes play a crucial role in the definition of Moving Load type analysis cases and Bridge Live load cases. The paper illustrates lanes for various load cases, as per SAP input, as depicted in Figure 3.

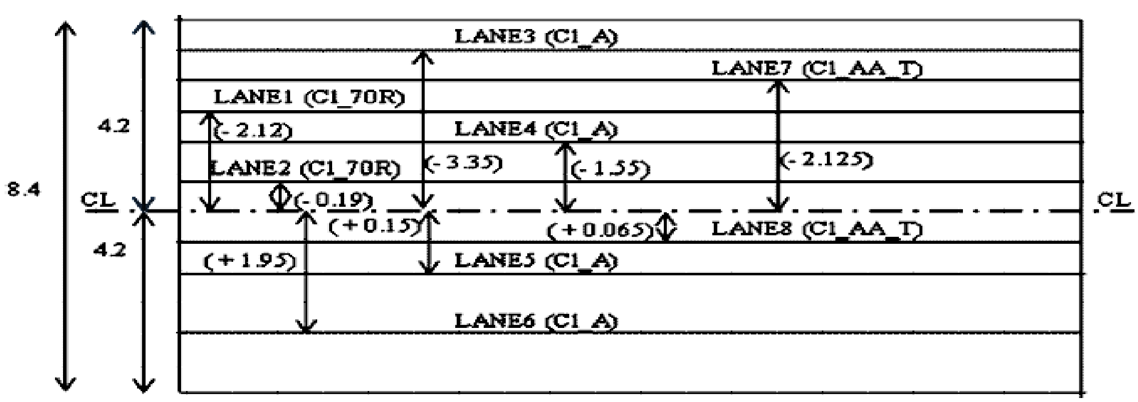


**Figure 3: Load Cases for Lanes Defined**

11) Vehicles: To analyze the bridge for live loads from vehicles, it's essential to define vehicles within the SAP2000 software. In SAP2000 version 11, vehicle loads are applied to the structure through lanes. The software offers numerous standard vehicle definitions integrated into the program. Additionally, users can create custom vehicle definitions using the General Vehicle feature. Each vehicle definition comprises one or more concentrated and/or uniform loads. Moreover, SAP2000 version 11 includes standards from the Indian Roads Congress (IRC) for loading specifications.

12) Analysis Cases: Various load cases must be considered when analyzing bridges, with special emphasis on vehicle live loads. Moving load analysis cases calculate influence lines for different quantities and assess the maximum and minimum response quantities by analyzing all permutations of lane loading. Multi-step static and multistep dynamic (direct integration time history) analysis cases are available to analyze one or more vehicles moving across the bridge at any given speed. These multi-step analysis cases are defined using specialized Bridge Live Load Cases, which specify the direction, starting time, and speed of vehicles moving along lanes.
The Finite Element Model prepared using the bridge wizard feature of SAP-2000 software is depicted in Figure 4. In this model, 4-noded 3D shell elements are utilized for the box section modeling. The results of the finite element models with different mesh sizes are compared, and a mesh size of 1.25 $m^2$ is ultimately adopted for modeling the structures. This mesh size optimization ensures an appropriate balance between computational efficiency and accuracy in the analysis of the bridge structures.

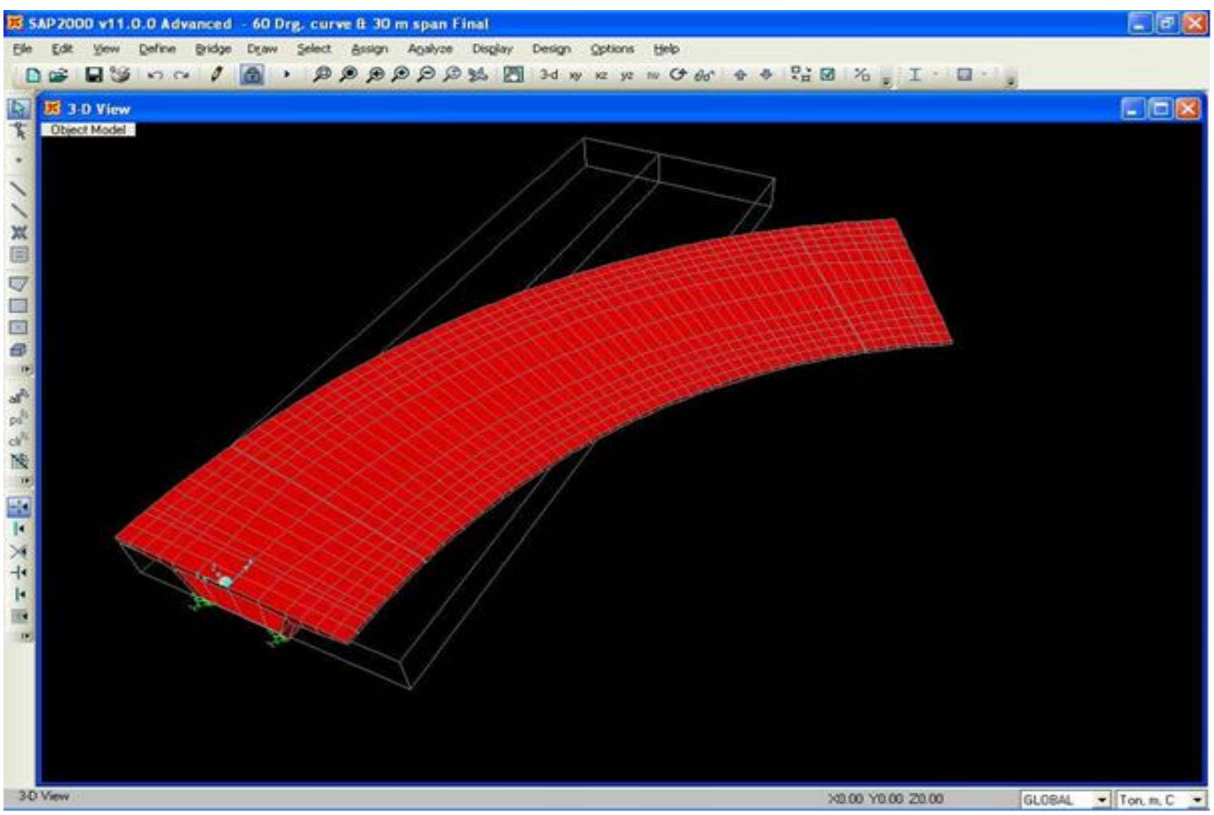


**Figure 4: 3D model of 30 m span and 60° curvature in SAP software**

## 4.0 PARAMETER SELECTION

In this paper, the parametric study focuses on two key parameters that have a significant influence on the behavior of curved bridges:

1) Span: The span of a bridge is a crucial parameter affecting its structural design and cost-effectiveness. Based on literature findings, RCC Box superstructures are deemed cost-effective within the span range of 15 m to 30 m. Therefore, this study considers span lengths within this range, with increments of 5 m (i.e., 15 m, 20 m, 25 m, and 30 m). The effect of varying span length on various behaviors of curved bridges is thoroughly examined and presented in this paper.

2) Degree of Curvature: The degree of curvature is a critical parameter influencing the behavior of curved bridge structures, particularly regarding stresses. Torsional stresses, in addition to axial, flexural, and shear stresses, become significant in curved bridges. Thus, this study investigates the effect of varying the degree of curvature from 0° to 90°, with increments of 10°, on the behavior of curved bridges.

Forty models of curved RCC box girders are developed, incorporating spans of 15 m, 20 m, 25 m, and 30 m, and degrees of curvature ranging from 0° to 90°. These models are analyzed using three-dimensional finite element modeling and analysis software, SAP 2000, under different load conditions and combinations. The study comprehensively examines various parameters, including bending, shear, axial, and torsional behaviors of curved RCC box bridges. Charts and tables are prepared to present the findings for the aforementioned parameters of curved bridges in the paper, providing valuable insights for bridge design and engineering practices.

## 5.0 FRAMING PROBLEM STATEMENT

The parametric study investigates curved bridges comprising two lanes with a main carriageway width of 7.5m, featuring RCC box-type superstructures. Span lengths range from 15m to 30m, with degrees of curvature varying from 0° to 90° in 10° increments. The material properties remain consistent across all models, while different cross-sections of the box-type superstructure are utilized for each span length. Support conditions simulate a simple span, with one end featuring a pinned support and the other end a roller support allowing horizontal movement. To counteract the effects of centrifugal force in the curvature, a 7% super elevation is provided for all models. Additionally, end diaphragms with a width of 0.4m are incorporated to reduce local effects and ensure a uniform distribution of large support reactions.

**Loads**

The following loads are considered:

1. Dead Load: This includes the self-weight of the box-type superstructure.

2. SIDL (Serviceability Limit State Dead Load): This encompasses the weight of crash barriers and wearing coats.

3. Live Load: IRC (Indian Roads Congress) loading for two-lane bridges is considered, comprising:

- One lane of Class-70R wheel loading
- Two lanes of Class-A loading
- One lane of Class-AA Tracked loading

4. Load Combinations: The analysis incorporates the following load combinations, with the worst effect considered:

- Dead Load (DL) + SIDL + Live Load (LL) (Maximum of Class 70R, Class A, and Class AA Tracked)

Live load moments are evaluated at the edge and center of the main carriageway, ensuring compliance with specified minimum clearances as per IRC guidelines. Results indicate that live loads at the edges govern, and thus, their effects are prioritized in the analysis.

## 6.0 OUTPUT

The results were obtained across different spans (15m, 20m, 25m, and 30m) and varying degrees of curvature (from 0° to 90° at 10° intervals). The analysis considered the total load, comprising Dead Load (DL), Superimposed Dead Load (SIDL), and Live Load (LL) at maximum intensity. Maximum Bending Moment (B.M.), Shear Force (S.F.), Torsion, and Axial Force were recorded along the entire section. The maximum B.M. and axial force were found at mid-span, the maximum S.F. at the edge, and the maximum torsion slightly away from the support.

Figure 5 illustrates the parametric variation of these actions across different spans (15m, 20m, 25m, and 30m) for various degrees of curvature, presented graphically for the entire box section under the combined load case of DL + SIDL + LL (Max.).

Moreover, Figure 6 displays multiplication factors for B.M., S.F., Axial Force, and Torsional Moment for spans ranging from 15m to 30m and for varying degrees of curvature across the entire box section, depicted graphically for the load case of DL + SIDL + LL (Max.).

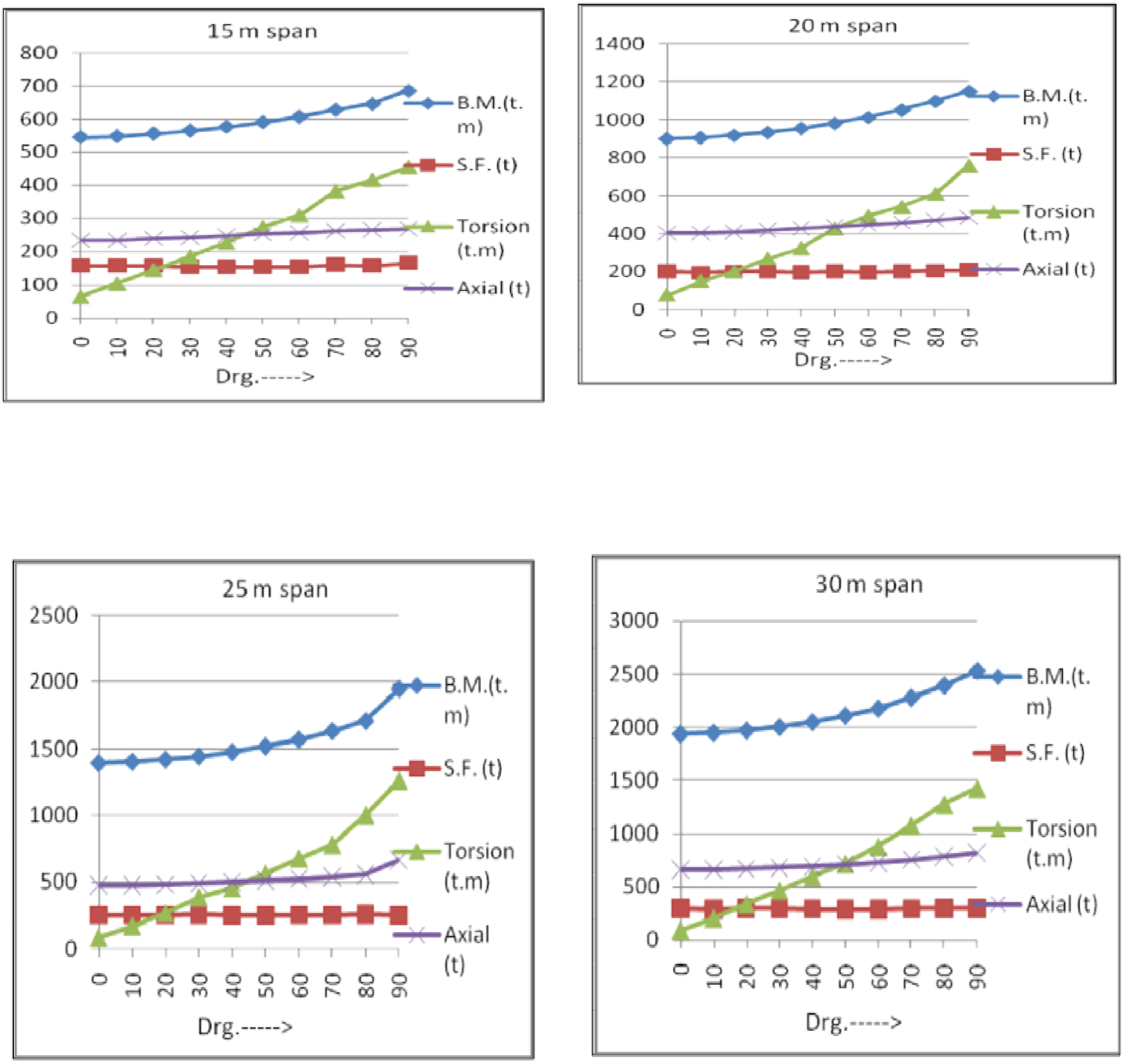


**Figure 5: B.M, S.F., Axial Force, and Torsional Moment across spans of 15m, 20m, 25m, and 30m, considering varying degrees of curvature for the entire box section.**

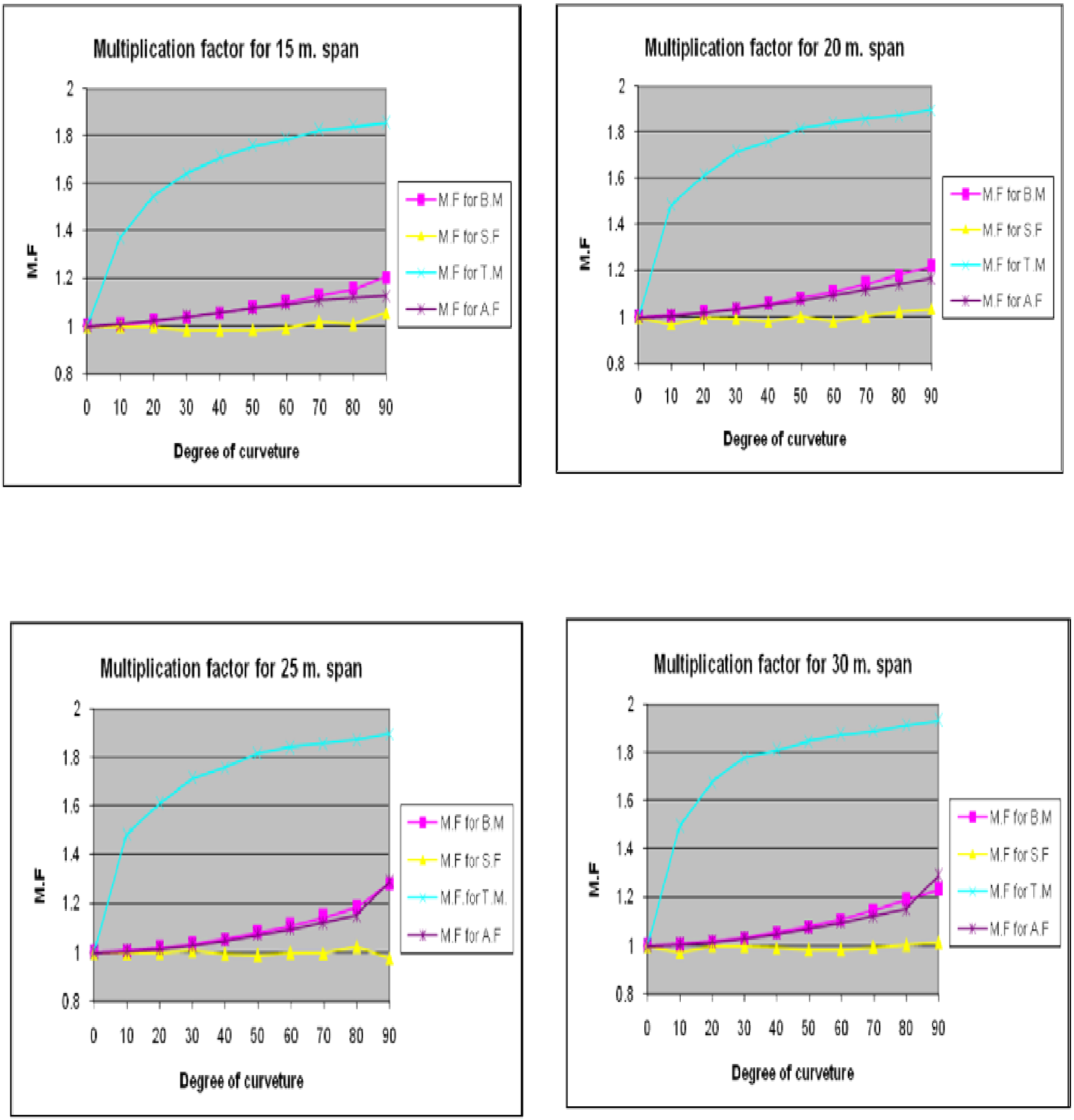


**Figure 6: Multiplication factors for B.M., S.F., Axial force & Torsional moment for spans of 15m, 20m, 25m and 30m and for varying degree of curvature for entire box.**

## 7.0 SUMMARY

The study conducted involved the creation of forty models, each representing a different span length (15m, 20m, 25m, and 30m) while maintaining consistent material properties. These models were subjected to varying degrees of curvature ranging from 0° to 90° at 10° intervals, under different load conditions and combinations as per IRC specifications. Finite element software SAP-2000 facilitated the analysis.

1) The graphical representation of the results indicates that the increase in torsion across different degrees of curvature is more pronounced compared to bending moments, shear forces, and axial carrying capacities. This suggests that the box section exhibits higher torsional stiffness, with a nonlinear variation concerning the degree of curvature.

2) The study offers multiplication factors for all parameters concerning varying degrees of curvature (from 10° to 90°) concerning a straight bridge (0°), and across different spans (ranging from 15m to 30m), as depicted in Figure 6. These factors can streamline the analysis by allowing the consideration of a straight bridge instead of a curved one. By multiplying the corresponding action of the straight bridge by the multiplication factor, preliminary design efforts can be simplified.

3) It's observed from the study that for different spans, the multiplication factor for varying degrees of curvature demonstrates linear variation concerning axial force and bending moment, typically ranging from 1.2 to 1.3 for 90° curvature. However, the multiplication factor for torsion moment exhibits nonlinear variation, typically ranging from 1.8 to 1.9 for 90° curvature. Interestingly, no multiplication factor is necessary for shear force, indicating its relatively stable behavior across different degrees of curvature and spans.

## 8.0 LITERATURE USED

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