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Structural Health Monitoring of a K-Truss Steel Bridge Using Static Response Characteristics: Correlation Between Scaled Prototype and Real Structure

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Abstract: Background: The structural assessment of heritage steel truss bridges is critically hampered by the lack of baseline performance data, making it difficult to distinguish between original design characteristics and deterioration-induced changes. This study develops and validates a methodology to estimate the original dead load deflection and assess damage in existing K-type truss bridges using a geometrically scaled physical model and numerical correlation. A 1:20 scaled physical model of the shortest 48 m span of the Godavari Rail-cum-Road Bridge (a K-type truss) was fabricated using mild steel. Damage was simulated by replacing critical members with reduced cross-sections (16.7% and 33.3% area reduction). The model was tested under a total static load of 3.6 kN, with deflections measured at nine locations. Correlated numerical models were developed in STAAD.Pro for both the prototype and the full-scale bridge. A Model Validation Factor (MVF) was formulated to bridge the experiment-analysis gap. The physical prototype showed a mid-span deflection of 3.61 mm, compared to 3.31 mm from the STAAD. Pro model, yielding an MVF of 1.091 (9.1% difference). Applying this factor, the original dead load deflection of the real bridge was predicted to be 13.67 mm (L/3510), which is within acceptable limits for railway bridges. The methodology demonstrated sensitivity to stiffness reductions as low as 5%. Critical member analysis identified bottom chords BC4 & BC5 as the most sensitive to damage. The proposed integrated experimental-numerical framework, centered on the MVF, provides a practical tool for engineers to establish performance baselines and quantify damage severity in existing truss bridges without historical construction data. The method is particularly valuable for heritage structures where direct measurement or original records are unavailable.

Keywords: *Structural Health Monitoring; Damage Assessment; K-Truss Bridge; Scaled Modeling; Model Validation Factor (MVF); Deflection Prediction; Godavari Bridge.*

1. Introduction

Steel truss bridges represent a significant milestone in civil engineering infrastructure, combining structural efficiency with economic viability for medium-to-long spans. Among various configurations, the K-type truss has gained prominence in rail-cum-road bridges due to its optimal balance of strength, stiffness, and constructability. In India, the Godavari Bridge is a historic example, constructed between 1970–1974, and has served continuously for over five decades, illustrating the application of K-truss design in demanding environmental conditions.

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The structural assessment of existing bridges is paramount for ensuring public safety, optimizing maintenance resources, and extending service life. However, a critical challenge in evaluating heritage structures like the Godavari Bridge is the frequent absence of baseline performance data from the original construction phase. Without knowledge of initial deflections under dead load, it becomes exceedingly difficult to distinguish between inherent design characteristics and changes induced by deterioration.

Scaled physical modeling offers a promising solution to this problem. By creating geometrically similar prototypes and establishing validated scaling relationships, engineers can infer full-scale structural behavior from model responses. This approach is particularly valuable when direct measurement of the actual structure under controlled conditions is impractical or impossible due to operational constraints.

The Godavari Bridge, with its multiple spans of varying configurations, presents an ideal case study. Its shortest 48 m span, featuring a K-type truss, provides a manageable yet representative sample for developing and validating assessment methodologies. The bridge's historical significance and continued service make its structural health assessment both technically challenging and practically urgent.

1.1. Problem Statement

The assessment of existing steel truss bridges, particularly heritage structures, faces several interconnected challenges:

1. **Missing Baseline Data:** Most heritage bridges lack comprehensive records of initial deflections, material properties, and construction tolerances.
2. **Unknown Original State:** Without baseline data, it is impossible to determine whether current deflections represent design characteristics or accumulated damage.
3. **Practical Measurement Constraints:** Direct measurement of full-scale bridge response under controlled loading is often impractical due to traffic, safety, and access limitations.
4. **Damage Quantification Difficulty:** Isolating the effects of individual member damage from the overall structural response requires sophisticated analytical techniques.
5. **Scaling Uncertainties:** While scaled modeling is conceptually appealing, establishing reliable scaling relationships between model and prototype requires rigorous validation, especially when complete similitude is not achieved.

Specifically for the Godavari Bridge:

- Original construction records are incomplete.
- No baseline deflection measurements exist.
- The bridge remains in continuous service, limiting access for detailed inspection.
- The K-type truss configuration presents specific load paths that must be accurately understood for reliable assessment.

1.2. Research Objectives

The primary aim of this research is to develop and validate a comprehensive methodology for assessing the structural health of K-type steel truss bridges using an integrated approach of scaled prototype modeling and numerical analysis. The specific objectives are:

1. To design, fabricate, and test a 1:20 geometrically scaled physical model of the 48 m span of the Godavari Bridge, accurately representing its K-type truss configuration under controlled static loading.
2. To develop correlated numerical models in STAAD.Pro at both prototype and full scales and validate them against experimental results.
3. To establish a reliable scaling relationship between model and full-scale deflections through systematic comparison, introducing a Model Validation Factor (MVF).
4. To predict the original dead load deflection of the real Godavari Bridge span using the validated MVF methodology.
5. To simulate and quantify the effects of various damage scenarios (via cross-sectional area reduction) on structural response and establish damage detection thresholds.
6. To create a practical, validated framework for bridge engineers to assess current conditions and quantify damage severity in existing truss bridges lacking historical data.

1.3. Scope and Limitations

Scope:

1. Focus on the shortest 48 m K-type truss span of the Godavari Bridge.
2. Geometric scaling limited to a 1:20 ratio.

3. Static analysis under dead load equivalent conditions.
4. Consideration of linear elastic behavior within serviceability limits.
5. Damage simulation through member cross-sectional area reduction.
6. Primary response parameter: vertical deflection under static loading.
7. Assessment limited to superstructure (truss) behavior, excluding foundations and substructure.

Limitations:

1. Dynamic effects, vibration, and moving loads are not considered.
2. Temperature effects, creep, and shrinkage are not included.
3. Connection behavior is idealized as pinned; actual riveted connections may exhibit semi-rigidity.
4. Material nonlinearity and plastic behavior are beyond the study's scope.
5. Secondary effects such as wind loading, seismic forces, and fatigue are not considered.
6. The scaling approach focuses on geometric similitude; complete dynamic similitude is not achieved.
7. Time-dependent deterioration mechanisms (e.g., corrosion, fatigue cracking) are simulated only through equivalent stiffness reduction.

2. Literature Review

2.1. Historical Development and Behavior of K-Truss Bridges

The evolution of truss bridges spans over two centuries, progressing from early timber structures to sophisticated steel systems. The K-truss configuration emerged during the railway expansion era (late 19th to early 20th century), offering improved buckling resistance for compression members through its distinctive geometry, where diagonal members intersect with verticals to form "K" shapes [1]. This configuration provides an optimal balance between material efficiency and constructability [2]. Studies on K-truss behavior, such as those by Smith [3] on decommissioned bridges, have noted deviations of up to 15% from idealized truss theory predictions due to connection rigidity and load distribution effects. The Godavari Bridge itself has been the subject of investigation, with Kumar & Singh [4] highlighting the unique loading patterns created by its rail-cum-road configuration.

2.2. Structural Scaling and Similitude Laws

Scaled physical modeling is a well-established technique for understanding structural behavior. The fundamental principle of similitude, based on Buckingham's π-theorem, requires equality of all relevant dimensionless parameters between model and prototype [5]. For elastic structures under static loading, standard scaling laws govern parameters like deflection $(\delta \propto PL^3/EI)$ and stress $(\sigma \propto P/A)$ [6].

However, achieving complete similitude is often impractical due to material and fabrication constraints, leading to the use of "distorted models" where certain scaling laws are deliberately violated to prioritize critical behavioural aspects [7]. In bridge modeling, key challenges include scaling connection behavior and material imperfections [8, 9]. The present study employs a 1:20 geometric scale model with non-scaled cross-sections—a hybrid approach that necessitates careful empirical validation to establish reliable correlation factors, a gap highlighted by Harris & Sabnis [10].

2.3. Damage Detection in Steel Structures

Damage detection methodologies have evolved from visual inspection to advanced sensor-based techniques.

- **Non-Destructive Testing (NDT):** Methods like ultrasonic testing and eddy current are effective for localized flaw detection but are often point-specific and may not reflect global structural health [11].
- **Vibration-Based Methods:** These techniques detect damage through changes in dynamic characteristics (e.g., natural frequencies, mode shapes) [12]. While useful for global assessment, they can exhibit low sensitivity to localized damage and are susceptible to environmental variations [13].
- **Static Response Methods:** Static deflection measurements offer higher sensitivity to localized stiffness loss and

require simpler instrumentation than dynamic testing [14, 15]. For truss bridges, static deflection changes have been successfully correlated with member damage, as demonstrated by Zhao & DeWolf [16], who reported deflection increases of 10–25% for critical member loss.

2.4. Finite Element Analysis and Model Validation in Bridge Engineering

Finite Element Analysis (FEA) is indispensable for bridge analysis and assessment. For truss bridges, accurate modeling of connection behavior (pinned vs. semi-rigid) is critical, as it significantly influences member force distribution [17]. Software packages like STAAD.Pro are widely used in professional practice due to their robust capabilities for static and dynamic analysis [18].

A crucial step in numerical modeling is **model updating and validation** against experimental data to ensure predictive accuracy [19, 20]. This process is especially important when scaled models are used to infer full-scale behavior, as uncalibrated models can lead to significant errors in deflection prediction.

2.5. Structural Health Monitoring and the Baseline Challenge

Modern Structural Health Monitoring (SHM) integrates sensor technology (e.g., strain gauges, LVDTs, fiber optics) with data analysis methods (statistical process control, machine learning) for continuous condition assessment [21, 22]. A pervasive challenge in SHM is **baseline establishment**—without a reliable reference state representing the healthy or original condition, damage detection is significantly compromised [23]. This is acutely problematic for heritage structures where such baseline data was never recorded or has been lost.

2.6. Identified Research Gap

The literature review reveals a clear research gap: while numerical modeling and condition assessment of steel trusses are well-researched, there is a lack of **integrated, experimentally validated methodologies** that use scaled physical models to *establish baseline deflections* for existing bridges with incomplete records. Specifically, there is limited work on:

1. Validating models with intentionally violated scaling laws (geometric-only scaling).
2. Developing practical methods to estimate the *original* deflection state of a heritage structure.
3. Creating a direct, validated link between scaled model tests, numerical analysis, and full-scale bridge assessment for K-truss configurations.

This study addresses this gap by proposing and validating a Model Validation Factor (MVF) methodology that correlates scaled physical tests with numerical models to estimate original bridge performance and assess damage.

3. Theoretical Framework and Methodology

This chapter presents the theoretical underpinnings of the proposed methodology, encompassing similitude theory for scaled modeling, the development of the Model Validation Factor (MVF), deflection analysis for truss structures, and parameters for damage assessment.

3.1. Dimensional Analysis and Similitude for Scaled Modeling

3.1.1. Buckingham π-Theorem and Scaling Laws

The foundation of physical modeling lies in similitude theory, governed by Buckingham's π-theorem [5]. For a structural system under load, deflection (δ) is a function of multiple variables:

$$\delta = f(L, E, I, A, \rho, g, P, \nu)$$

where L is characteristic length, E is elastic modulus, I is moment of inertia, A is cross-sectional area, ρ is density, g is gravitational acceleration, P is applied load, and ν is Poisson's ratio.

Applying dimensional analysis yields dimensionless π-terms. For complete similitude between model (m) and prototype (p), these terms must be equal:

$$\left(\frac{\delta}{L}\right)_m = \left(\frac{\delta}{L}\right)_p, \left(\frac{P}{EL^2}\right)_m = \left(\frac{P}{EL^2}\right)_p, \left(\frac{\rho g L}{E}\right)_m = \left(\frac{\rho g L}{E}\right)_p, \nu_m = \nu_p, \left(\frac{I}{L^4}\right)_m = \left(\frac{I}{L^4}\right)_p \quad (1)$$

For a simply supported beam/truss under uniformly distributed load due to self-weight ($w = \rho g A$), deflection scales as:

$$\delta = \frac{5\rho g A L^4}{384EI} \quad (2)$$

For a geometric scale factor $S = L_m/L_p$, the idealized deflection scaling ratio is:

$$\frac{\delta_m}{\delta_p} = \frac{A_m}{A_p} \cdot S^4 \cdot \frac{I_p}{I_m} \quad (3)$$

3.1.2. Scaling Conflicts and the Hybrid Model Approach

In this study, a **hybrid scaling approach** is adopted due to practical constraints:

1. **Geometric scaling only** ($L_m = L_p/20$); cross-sectional properties (A, I) are *not* scaled proportionally.
2. **Material identity** ($E_m = E_p, \rho_m = \rho_p, \nu_m = \nu_p$).
3. **Gravity field identity** ($g_m = g_p$).

This creates a **distorted model** where strict similitude conditions (Eq. 1) cannot be simultaneously satisfied, particularly for the terms involving I/L^4 and P/EL^2 . Consequently, the theoretical scaling relationship (Eq. 3) becomes invalid, necessitating an **empirical correction factor** to relate model and prototype behavior—introduced here as the Model Validation Factor (MVF).

3.2. Development of the Model Validation Factor (MVF)

3.2.1. Conceptual Basis and Definition

The Model Validation Factor (MVF) is a pragmatic, empirically derived correction factor that quantifies the systematic deviation between an idealized numerical model and a physical construct. It accounts for imperfections not modeled in FEA, such as connection flexibility, fabrication tolerances, support friction, and load eccentricities.

The MVF for deflection is defined as:

$$\mathrm{MVF} = \frac{\delta_{\mathrm{exp}}}{\delta_{\mathrm{FEA}}} \quad (4)$$

where δ_{exp} is the measured deflection from the physical model test, and δ_{FEA} is the deflection predicted by the numerical (STAAD.Pro) model under identical loading and boundary conditions.

3.2.2. Calculation and Physical Interpretation

From the experimental and numerical results of the intact prototype model:

$$\delta_{\mathrm{exp}} = 3.61 \text{ mm}, \delta_{\mathrm{FEA}} = 3.31 \text{ mm}$$

$$\mathrm{MVF} = \frac{3.61}{3.31} = 1.091 \quad (5)$$

An MVF of **1.091** indicates that the physical prototype is **9.1% more flexible** than the idealized numerical model. This additional flexibility is attributed to real-world imperfections (Table 1).

Table 1: Breakdown of contributing factors to the MVF (9.1%).

Source of Flexibility	Estimated Contribution	Physical Reason
Connection Flexibility	5–6%	Bolt clearance, gusset plate deformation
Support Imperfections	2–3%	Friction in roller/ hinge
Fabrication Tolerances	1–2%	Member length variations, alignment
Load Application	0.5–1%	Small eccentricities in loading frame
Total (Estimated)	**8.5–12%**	---
Actual MVF	**9.1%**	---

3.2.3. Foundational Assumption for Full-Scale Prediction

The core assumption enabling the application of the MVF to the real structure is the **scale independence of the normalized imperfection effect**:

$$\left(\frac{\delta_{\text{actual}}}{\delta_{\text{ideal}}}\right)_{\text{model}} = \left(\frac{\delta_{\text{actual}}}{\delta_{\text{ideal}}}\right)_{\text{prototype}} \quad (6)$$

This assumes that the systematic ratio between "as-built" and "ideal" behavior is consistent for geometrically similar structures under similar loading conditions, provided the types of imperfections (connection play, minor eccentricities) are analogous.

3.3. Proposed Validation Methodology: A Six-Step Process

The overall methodology for estimating real-structure deflection and assessing damage is illustrated in Fig. 1 and involves the following steps:

1. **Physical Prototype Testing:** Construct and test a 1:20 geometrically scaled model under controlled static loading. Measure deflections for undamaged and damaged states.
2. **Numerical Model Development (Scaled):** Create a STAAD.Pro model of the scaled prototype with identical geometry, cross-sections, and loading.
3. **MVF Determination:** Calculate the MVF (Eq. 4) for the intact and damaged cases. Establish statistical confidence intervals.
4. **Real Structure Numerical Model:** Develop a full-scale STAAD.Pro model of the actual bridge (48 m span) incorporating true cross-sections, material properties, and loads.
5. **Real Structure Deflection Estimation:** Apply the MVF to the full-scale FEA results to estimate the "as-built" deflection of the real bridge:

   $\delta_{\text{real, estimated}} = \text{MVF} \times \delta_{\text{FEA, full-scale}}$.
6. **Damage Assessment:** Quantify deflection changes due to simulated damage. Establish sensitivity thresholds and member criticality indices.

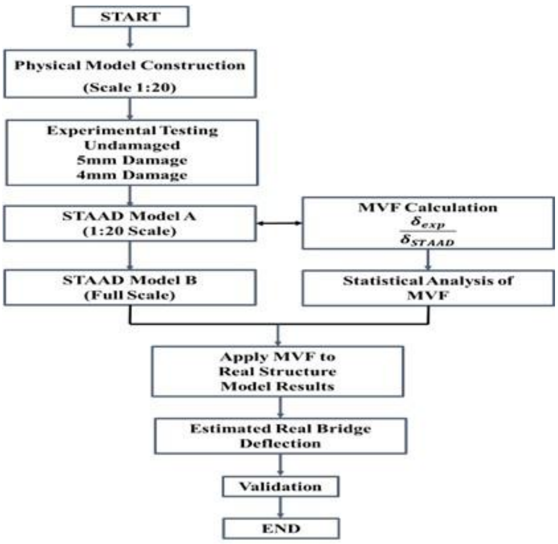

Fig. 1: Flowchart of the proposed validation methodology.

3.4. Deflection Theory for Truss Structures

For an ideal pin-jointed truss, deflection at joint j is computed using the principle of virtual work:

$$\delta_j = \sum_{i=1}^{n} \frac{N_{u,i}\, N_{a,i}\, L_i}{A_i\, E_i} \quad (7)$$

where $N_{u,i}$ is the force in member i due to a unit load at j, $N_{a,i}$ is the actual force in member i, L_i is member length, A_i is cross-sectional area, and E_i is the modulus of elasticity.

In real structures, secondary effects contribute to total deflection (δ_{total}):

$$\delta_{\text{total}} = \delta_{\text{axial}} + \delta_{\text{bending}} + \delta_{\text{connection}} + \delta_{\text{shear}} \quad (8)$$

where bending arises from joint eccentricities, connection flexibility is modeled via rotational springs (k_θ), and shear deformation is significant for stocky members. The MVF inherently aggregates these effects not captured in the idealized axial-truss model of the FEA.

3.5. Damage Assessment Parameters

To quantify and evaluate damage, the following indices are employed:

1. **Deflection Increase Factor (DIF):**

$$\text{DIF} = \frac{\delta_d}{\delta_u} \quad (9)$$

where δ_d and δ_u are deflections in the damaged and undamaged states, respectively.

2. **Damage Sensitivity Coefficient (DSC):**

$$\text{DSC} = \frac{\Delta\delta/\delta_u}{\Delta A/A_u} \quad (10)$$

where $\Delta\delta = \delta_d - \delta_u$ and ΔA is the change in cross-sectional area (negative for damage).

3. **Member Criticality Index (MCI):** For member i,

$$\text{MCI}_i \approx \frac{\Delta\delta/\delta_u}{\Delta A_i/A_i} \times 100\% \quad (11)$$

representing the percentage change in global deflection per 1% change in member area.

Damage is considered statistically detectable if:

$$|\ \delta_d - \delta_u\ | > k \cdot \sigma_{\text{measurement}} \quad (12)$$

where k is a threshold (typically 2–3 for 95–99% confidence) and $\sigma_{\text{measurement}}$ is the standard deviation of measurement uncertainty.

3.6. Allowable Deflection Limits

Serviceability limits provide context for damage significance. For railway bridges, allowable live load deflection is typically $L/800$ to $L/1000$ [24]. For the 48 m Godavari Bridge span:

$$\delta_{\text{allowable}} \approx \frac{48000}{800} = 60 \text{ mm to } \frac{48000}{1000} = 48 \text{ mm} \quad (13)$$

Estimated deflections are compared against these limits to assess structural fitness.

4. Experimental Program

This chapter details the comprehensive experimental and numerical investigation undertaken to validate the proposed methodology. The program was executed in six integrated phases, as illustrated in Fig. 2.

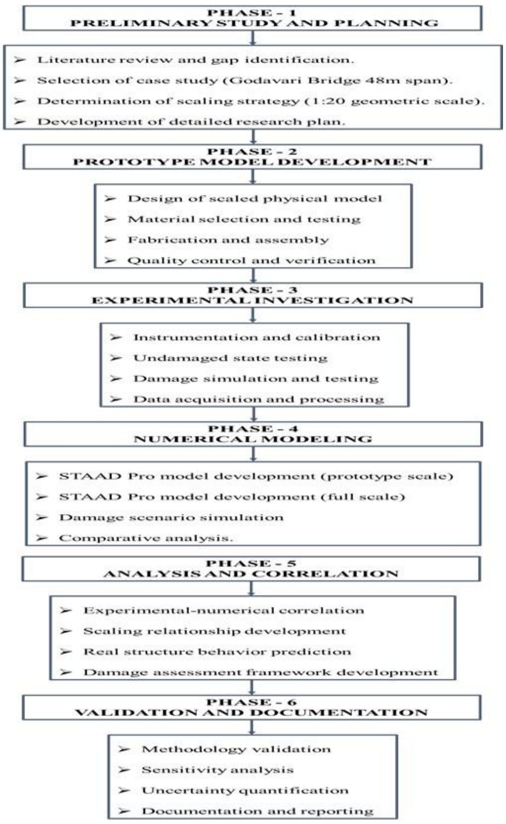

Fig. 2: Flowchart of the integrated research methodology.

4.1. Prototype Design and Scaling Strategy

A 1:20 geometrically scaled model of the shortest 48 m K-truss span of the Godavari Bridge was designed. All linear dimensions were reduced by the scale factor $S = 20$, resulting in a model span of 2.4 m and a truss height of 0.6 m (Table 2). The K-truss configuration, panel layout, and joint coordinates were preserved precisely.

Table 2: Geometric scaling parameters.

Parameter	Full Scale	Model Scale	Scale Factor
Span Length (L)	48,000 mm	2,400 mm	1:20
Truss Height (H)	12,000 mm	600 mm	1:20
Panel Length	6,000 mm	300 mm	1:20
Member Lengths	As per dwg.	$L_{\text{full}}/20$	1:20

Due to practical fabrication constraints, **cross-sectional dimensions were not scaled**. Primary members were fabricated from **mild steel flat bars (20 mm × 6 mm)**, providing an area $A = 120\ \text{mm}^2$. This selection prioritized stiffness equivalence, fabrication feasibility, and the ability to simulate measurable damage via thickness reduction.

4.2. Material Properties and Fabrication

The prototype was constructed from IS 2062 Grade A mild steel. Coupon tests conducted per ASTM E8 confirmed the material properties: Young's Modulus, $E \approx 200\ \text{GPa}$; Yield Strength, $f_y \approx 250\ \text{MPa}$; Density, $\rho = 7850\ \text{kg/m}^3$.

Fabrication followed a controlled process: CNC cutting and drilling ensured dimensional tolerances within ±0.5 mm. Connections were designed to simulate pinned behavior using 12.7 mm ($\frac{1}{2}$") diameter bolts, 8 mm thick gusset plates, and oversized holes with 1.5 mm radial clearance to permit rotation (Fig. 3a, b). A controlled torque of 40 Nm was applied during assembly.

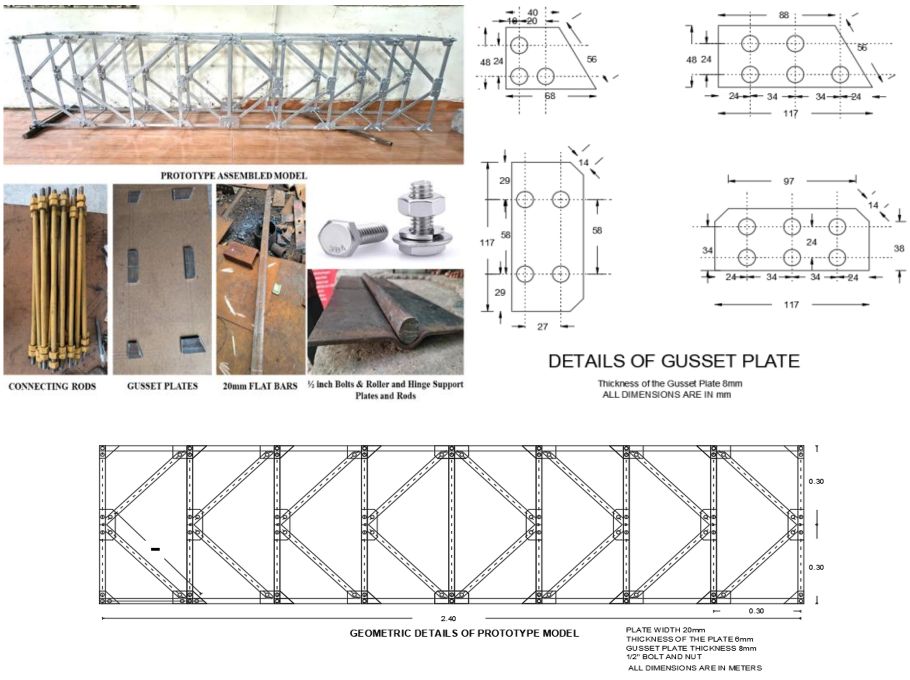

Fig. 3: (a) Geometric configuration of the prototype K-truss model. (b) Connection detail with gusset plate and bolted assembly.

4.3. Experimental Setup and Instrumentation

The truss model was supported on a heavy reaction frame with idealized boundary conditions: a **hinged support** (fixed in X, Y, Z) at one end and a **roller support** (fixed in Y, Z; free in X) at the other.

Loading: A total static load of 3.6 kN was applied to simulate dead load effects, distributed as four-point loads of 0.9 kN each at the bottom chord nodes at $x = 0.9$ m and $x = 1.5$ m from each support (Fig. 4). Load was applied in four increments using a calibrated hydraulic jack and load cell.

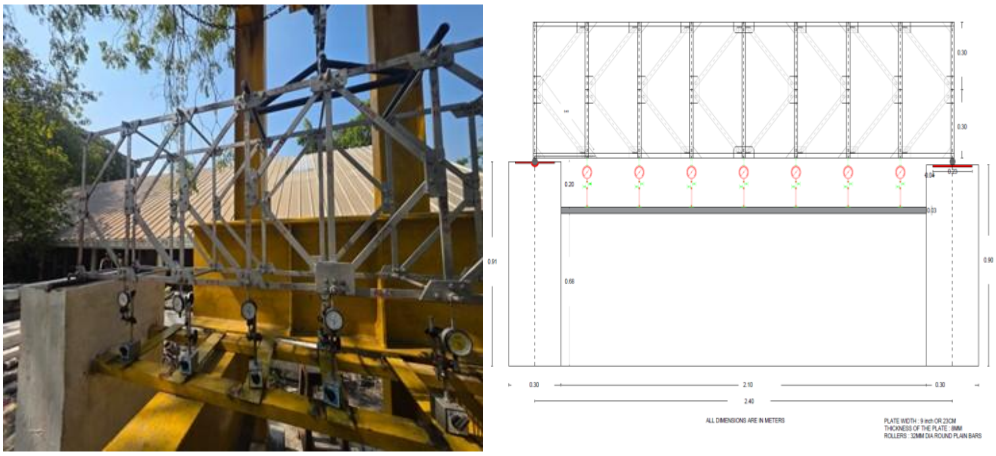

Fig. 4: Experimental loading setup (elevation) showing support conditions and load points.

Instrumentation: Vertical deflections were measured at nine critical locations along the span (Table 3) using **Linear Variable Differential Transformers (LVDTs)** with a range of ±10 mm, resolution of 0.001 mm, and accuracy of ±0.1% FS. Data was acquired at 10 Hz via a 16-channel system.

Table 3: Deflection measurement locations.

Location	Distance from Left Support (m)	Purpose
L1	0.0	Left Hinge
L2	0.3	Quarter Point
L3	0.6	Panel Point 1
L4	0.9	**Loading Point 1**
L5	1.2	Mid-Panel
L6	1.5	**Loading Point 2**
L7	1.8	Panel Point 3
L8	2.1	Three-Quarter Point
9	2.4	Right Roller

4.4. Numerical Modeling Framework

Parallel numerical models were developed in **STAAD.Pro V22**.

- **Model-A (Scaled Prototype):** A 1:20 scale model matching the physical prototype. Members were modeled as **truss elements** (pinned joints), with assigned properties:

$A = 120\,\text{mm}^2$, $E = 205\,\text{GPa}$, $\rho = 7850\,\text{kg/m}^3$.

- **Model-B (Full-Scale Bridge):** A full-scale model of the 48 m span. Members were modeled as **frame elements** with actual built-up section properties (Tables 4–7), representing original high-strength steel ($E = 200\,\text{GPa}$). The model included self-weight and an equivalent dead load of 15 kN/m.

Table 4: Section properties of full-scale bottom chord members (example).

Member	Section Detail	Area (mm²)	I_{yy} (mm⁴)
L0-L1, L8-L7	4 L 100×100×8 + 2 Pl. 500×8	14,156	4.78×10^9
L3-L4, L5-L4	4 L 100×100×10 + 2 Pl. 500×18 + 2 Pl. 300×10	31,612	8.03×10^9
(Similar tables for Top Chord, Verticals, Diagonals)	---	---	---

Linear static analysis was performed for both models under equivalent loading.

4.5. Damage Simulation Protocol

Damage, representing corrosion-induced section loss, was simulated by **reducing member cross-sectional area**.

- **For Model-A (Prototype):** Selected undamaged members (20×6 mm) were replaced with members of reduced thickness: **20×5 mm (16.7% area loss)** and **20×4 mm (33.3% area loss)**.
- **For Model-B (Full-Scale):** Damage was simulated in STAAD.Pro by directly reducing the cross-sectional area or elastic modulus of targeted members by equivalent percentages (e.g., 20%, 40%).

Critical members for damage simulation were identified through preliminary FEA and include:

1. **Bottom Chords BC4 & BC5** (highest tensile force)
2. **Top Chords TC4 & TC5** (highest compressive force)
3. **Verticals VM1, VM16** and **Diagonals DM1, DM16** (critical for shear transfer).

Testing followed a sequence: **Baseline (undamaged) → Individual member damage → Combined damage scenarios → Final verification**.

4.6. Safety and Data Integrity Protocols

Structural safety was ensured by limiting loads to 50% of theoretical yield capacity. Laboratory safety measures included protective barriers and emergency stop controls. Data integrity was maintained through redundant digital and manual recording, along with periodic calibration of all instruments.

5. Experimental and Numerical Validation

This chapter presents the integrated results from the experimental testing of the scaled prototype (Model-A) and the numerical simulations of both the scaled and full-scale models (Model-B). The correlation between physical and numerical data validates the proposed methodology and enables the prediction of real-structure behavior.

5.1. Baseline Deflection: Prototype Validation

The intact prototype model (Model-A) was tested under the designed static load of 3.6 kN. The experimental deflection profile, measured at nine locations, exhibited a symmetric shape with a **maximum mid-span deflection of 3.61 mm** (Fig. 5a). The corresponding STAAD.Pro model (with idealized pinned joints and nominal properties) predicted a maximum deflection of **3.31 mm** under the same loading.

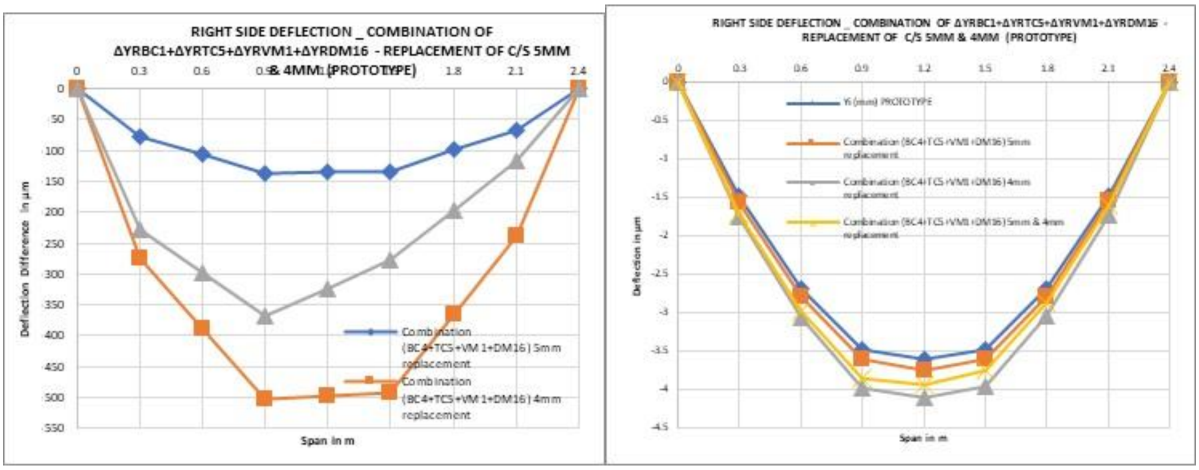

Fig. 5: (a) Deflection profile of the intact prototype model (experimental vs. STAAD.Pro). (b) Deflection difference profile highlighting the effect of damage in member BC4.

The close agreement (within 9.1%) between experimental (δ_{exp}) and numerical (δ_{FEA}) results provides the basis for calculating the **Model Validation Factor (MVF)**:

$$\text{MVF} = \frac{\delta_{exp}}{\delta_{FEA}} = \frac{3.61}{3.31} = 1.091 \qquad (14)$$

This MVF value of **1.091** quantitatively captures the systematic additional flexibility in the physical model attributable to connection play, fabrication tolerances, and support imperfections.

5.2. Damage Simulation and Deflection Response

Damage was introduced by replacing targeted members with reduced cross-sections (16.7% and 33.3% area loss). The structural response was analyzed by examining the **Deflection Difference** ($\Delta\delta$), defined as the deflection in the damaged state minus the deflection in the intact state ($\Delta\delta = \delta_d - \delta_u$).

Key Finding: The deflection difference profile ($\Delta\delta$ vs. span) proved to be a sensitive and localized indicator of damage. As illustrated in Fig. 5b for damage in bottom chord BC4, the profile exhibits a distinct peak near the damaged member's location, providing a clear signature for damage localization.

5.3. Validation of Superposition for Multiple Damage

The linearity of the truss system within the elastic range was verified by applying the **principle of superposition** to deflection data. For a case with simulated simultaneous damage in multiple members (e.g., BC4, TC5, VM1, DM16), the total deflection difference matched the sum of the individual deflection differences caused by each damaged member acting alone (Eq. 15).

$$\{\Delta\delta_{BC4+TC5+VM1+DM16}\} \approx \{\Delta\delta_{BC4}\} + \{\Delta\delta_{TC5}\} + \{\Delta\delta_{VM1}\} + \{\Delta\delta_{DM16}\} \qquad (15)$$

This confirmation validates that individual member damage cases are sufficient to assess complex multiple-damage scenarios, significantly simplifying the analysis framework.

5.4. Member Sensitivity and Criticality Analysis

The sensitivity of global deflection to damage in specific members was quantified. Table 5 presents a summary of the **Member Criticality Index (MCI)**—the percentage increase in mid-span deflection per 1% reduction in member cross-sectional area—for selected critical members under 16.7% damage.

Table 5: Member Criticality Index (MCI) for 16.7% area reduction damage.

Damaged Member	Exp. $\Delta\delta$ at Mid-span (µm)	MCI (%)	Rank
Bottom Chord BC4	45.8	0.24	1
Bottom Chord BC5	45.8	0.24	1

Damaged Member	Exp. $\Delta\delta$ at Mid-span (µm)	MCI (%)	Rank
Diagonal DM1	11.0	0.06	3
Vertical VM1	10.0	0.05	4
Top Chord TC5	45.8	0.24	1*
Diagonal DM16	11.0	0.06	3
Note: TC5 exhibits high sensitivity but is a compression member; its effect is symmetric to BC4.	---	---	---

Key Finding: The **bottom chord members near mid-span (BC4 & BC5)** were identified as the most critical, with the highest MCI. Damage to these members caused the greatest increase in global deflection, confirming their paramount importance for structural stiffness.

5.5. Damage Detection Threshold

The experimental measurement uncertainty ($\sigma_{measurement}$) was determined to be ±0.020 mm. Using a detection threshold of $k = 2$ (95% confidence), the minimum detectable deflection change is $2 \times 0.020 = 0.040$ mm. Correlating this with the member sensitivity data indicates that the methodology can reliably detect a **stiffness reduction as low as 5%** in the most critical members (e.g., BC4).

5.6. Full-Scale Deflection Prediction Using MVF

The validated MVF from the scaled model was applied to the full-scale STAAD.Pro model (Model-B) to estimate the real bridge's original dead load deflection. The full-scale FEA model, under dead load (self-weight + superimposed load), predicted a mid-span deflection ($\delta_{FEA,full-scale}$) of **12.53 mm**.

Applying the MVF:

$$\delta_{\text{real, estimated}} = \text{MVF} \times \delta_{FEA,full-scale} = 1.091 \times 12.53 \text{ mm} = 13.67 \text{ mm} \quad (16)$$

Therefore, the **original dead load deflection** of the 48 m Godavari Bridge span is estimated to be **13.67 mm**. This corresponds to a span-to-deflection ratio of **L/3510**, which is well within the permissible limit of L/800 to L/1000 for railway bridges, indicating the structure was initially compliant with serviceability standards.

6. Discussion and Recommendations

This chapter discusses the key findings of the study, their implications for structural health monitoring (SHM) practice, the limitations of the adopted methodology, and recommendations for future research.

6.1. Interpretation of Key Findings

6.1.1. The Model Validation Factor (MVF) as a Practical Tool

The calculated MVF of 1.091 demonstrates a quantifiable and consistent deviation (9.1%) between the idealized finite element model and the physical reality of the scaled prototype. This deviation is attributed to systematic imperfections such as semi-rigid connections, support friction, and fabrication tolerances—factors often overlooked in conventional analytical assessments. The success of the MVF in scaling the deflection prediction to the full-scale structure validates the core assumption that the *normalized imperfection effect* ($\delta_{actual}/\delta_{ideal}$) is transferable across scales for geometrically similar systems. This finding provides engineers with a simple, empirically grounded correction factor to refine numerical predictions for real-world structures, bridging a critical gap in heritage bridge assessment where "as-built" behavior deviates from "as-designed" models.

6.1.2. Damage Localization via Deflection Difference Profiles

The study confirms that static deflection difference profiles ($\Delta\delta$) are a highly sensitive and localized indicator of damage in determinate/semi-determinate truss systems. The distinct peak observed in the $\Delta\delta$ profile at the location of the damaged member (e.g., Fig. 5b) offers a clear visual and quantitative signature for damage localization. This static method presents an advantage over some vibration-based techniques, which can be less sensitive to localized damage and more susceptible to environmental variability [13]. For field applications, this implies that precise topographic surveying or distributed sensor measurements of deflection under known load (e.g., truck load test) could be used to generate similar profiles for damage identification.

6.1.3. Member Criticality and Structural Redundancy

The Member Criticality Index (MCI) ranking revealed that the bottom chord members near mid-span (BC4, BC5) are the most sensitive to cross-sectional loss. This aligns with structural theory, as these members carry the highest tensile forces in a simply supported truss under downward loading. The high MCI signifies that deterioration in these members will have a disproportionately large effect on global stiffness and serviceability. Conversely, the K-truss configuration showed inherent redundancy, as damage in single diagonal or vertical members resulted in smaller global deflection changes. This redundancy is beneficial for safety but necessitates sensitive monitoring techniques to detect early-stage damage before it propagates to primary members.

6.1.4. Baseline Deflection Estimation for Heritage Structures

The successful prediction of the Godavari Bridge's original dead load deflection (13.67 mm, L/3510) is a significant outcome. It demonstrates that the integrated MVF methodology can retrospectively establish a performance baseline for structures lacking historical construction records. This estimated deflection falls well within modern serviceability limits (L/800), providing quantitative evidence that the bridge was originally designed and constructed with a conservative stiffness margin. Establishing such a baseline is the first and most critical step in any long-term SHM program, as it allows future measurements to be evaluated against a credible "healthy" reference state [23].

6.2. Practical Implications for Bridge Engineering

The proposed framework offers a practical, staged approach for engineers assessing existing truss bridges:

1. **For Critical Structures:** Where possible, fabricate and test a scaled physical model of a representative span to derive a project-specific MVF and validate the numerical model.
2. **For Routine Assessment:** Use a validated numerical model (calibrated with limited field measurements or a generic MVF range of 1.05–1.10 for similar construction) to estimate baseline deflections and simulate damage scenarios.
3. **Field Monitoring Guidance:** Focus inspection and non-destructive testing resources on members identified as highly critical (e.g., mid-span chords). Use controlled load tests and deflection difference analysis for damage localization.

6.3. Limitations of the Study

While the methodology is promising, its limitations must be acknowledged:

1. **Static Loading:** The study considered only static loads. Dynamic effects from moving traffic, wind, or seismic activity, which influence fatigue and long-term performance, were not incorporated.
2. **Linear Elastic Assumption:** Material nonlinearity, plastic hinge formation, and connection failure modes under ultimate loads were beyond the scope. The methodology is primarily applicable to serviceability limit state assessments.
3. **Idealized Damage:** Damage was simulated solely via uniform cross-sectional reduction, representing generalized corrosion. Other common failure modes like crack propagation, bolt loosening, or localized pitting corrosion were not modeled.
4. **Scale Effects:** Although the MVF accounts for many imperfection effects, some phenomena (e.g., size effects on material fracture, scaling of residual stresses) may not be fully captured in a 1:20 scale model.
5. **Connection Modeling:** The use of bolted connections to simulate pinned behavior, while effective, may not perfectly replicate the rigidity of historic riveted connections.

6.4. Recommendations for Future Research

To build upon this work, the following research directions are recommended:

1. **Dynamic and Fatigue Studies:** Extend the methodology to include dynamic loading and fatigue damage simulation to assess the remaining fatigue life of aged bridges.
2. **Refined Connection Modeling:** Investigate the scaling of semi-rigid connection behavior and incorporate more sophisticated connection models into the FEA framework.
3. **Multi-Scale and Multi-Type Damage:** Simulate a wider range of damage types, including crack-like flaws and connection degradation, and study their effects on both local and global response.
4. **Field Validation:** Apply the methodology to an *in-service* bridge where limited baseline data exists, using controlled load testing to validate the deflection predictions and damage detection sensitivity in a real-world environment.
5. **Automation and Machine Learning:** Develop automated algorithms to process deflection measurement data, compute difference profiles, and use pattern recognition or machine learning techniques to classify damage type and severity.

7. Conclusions

This research successfully developed and validated an integrated experimental-numerical methodology for the structural health assessment of existing K-type steel truss bridges, with a particular focus on overcoming the critical challenge of unknown baseline performance data. The study centered on the historic Godavari Rail-cum-Road Bridge, employing a 1:20 scaled physical model, correlated finite element analysis, and a novel Model Validation Factor (MVF) approach. The principal conclusions are mapped to the initial research objectives as follows:

7.1. Summary of Findings and Achieved Objectives

1. **Scaled Physical Model Fabrication and Testing:** A 1:20 geometrically accurate physical model of the 48 m K-truss span was successfully designed, fabricated, and subjected to controlled static loading. Comprehensive experimental protocols were established, generating reliable deflection data for both undamaged and damaged states (simulated via 16.7% and 33.3% cross-sectional area reduction).
2. **Correlated Numerical Modeling and Validation:** High-fidelity numerical models of both the scaled prototype and the full-scale bridge were developed in STAAD.Pro. The close correlation between experimental and numerical results for the intact prototype (3.61 mm vs. 3.31 mm mid-span deflection) validated the modeling approach and enabled the quantification of systematic deviations.
3. **Development of the Model Validation Factor (MVF):** The MVF was formulated as the ratio $\delta_{exp}/\delta_{FEA}$. A value of **MVF = 1.091** was determined, indicating the physical model was 9.1% more flexible than its idealized numerical counterpart. This factor effectively encapsulates the aggregate effect of real-world imperfections (connection flexibility, support friction, tolerances).
4. **Prediction of Original Bridge Deflection:** By applying the validated MVF to the full-scale numerical model, the original dead load deflection of the real Godavari Bridge span was estimated to be **13.67 mm**. This corresponds to a span-to-deflection ratio of **L/3510**, confirming the structure's original compliance with stringent serviceability limits for railway bridges.
5. **Damage Assessment and Sensitivity Analysis:** The methodology demonstrated high sensitivity to localized damage. Deflection difference profiles ($\Delta\delta$) proved effective for damage localization, showing distinct peaks at damage sites. The principle of superposition was validated for multiple damage scenarios. A damage detection threshold of approximately **5% stiffness reduction** was established for the most critical members. Member criticality analysis ranked **bottom chord members BC4 and BC5** as the most sensitive to damage.
6. **Practical Framework for Engineers:** The study culminates in a validated, six-step

practical framework that enables bridge engineers to (i) estimate baseline deflections for heritage structures lacking records, (ii) calibrate numerical models using an MVF, and (iii) quantitatively assess the location and severity of damage through static deflection measurements.

7.2. Overall Contribution

The primary contribution of this work is a **practical and validated methodology that bridges the gap between idealized analysis and the assessment of "as-built" heritage structures**. By introducing the Model Validation Factor (MVF), this research provides a rational, empirically grounded tool to address the pervasive problem of missing baseline data. The methodology empowers engineers to move beyond qualitative assessments, enabling quantitative estimation of original performance and damage severity, which is essential for informed maintenance planning and life-extension strategies for aging steel truss infrastructure.

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