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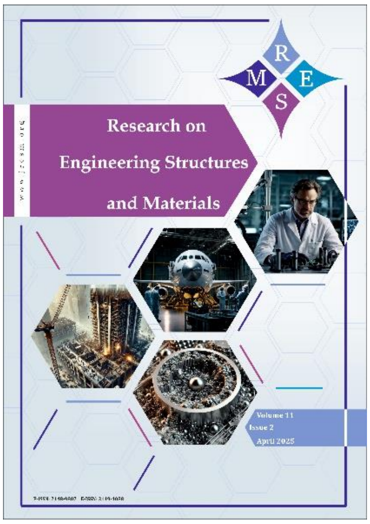

Optimum and efficient design of steel foot over bridges

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Research Article

Optimum and efficient design of steel foot over bridges

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Abstract

This work used the Finite Element Method (FEM) to estimate the shear force for a blind shear ram type blowout preventer. In recent years, significant advancements have been made in the design of Foot Over Bridges (FOBs) through the utilization of advanced analytical methods, innovative materials, and novel bridge concepts. FOBs have gained popularity in urban India due to their ability to facilitate safe pedestrian crossings without disrupting vehicular traffic flow, thereby enhancing pedestrian safety in areas with heavy traffic. This research focuses on the development of an economically optimized steel FOB design specifically tailored for the Mumbai region. The primary objectives are to ensure durability, stability, safety, and cost-effectiveness in the design. The study involves modelling the typical span of a skywalk structure using STAAD Pro, followed by comprehensive analysis and design iterations for various configurations based on real-world spans of existing pedestrian bridges. Static loading conditions are applied to the FOB models, allowing important characteristics like weight, number of joints, number of members, weld lengths, painting surface area, and natural frequency of pedestrian bridges to be evaluated. These factors are carefully contrasted to determine the bridge design that is the most economical. Additionally, vibration tests are conducted on two selected skywalks to assess their compliance with serviceability criteria. The research scrutinizes the utilization ratio of members in the bridge structures and explores variations in section sizes within the design to achieve the optimal configuration. The findings are presented in detail, offering valuable insights into the process of identifying the most economical FOB design from the skywalks in the Mumbai suburban region. This study contributes to the enhancement of pedestrian infrastructure in urban India by delivering a robust and cost-efficient FOB design approach.

1. Introduction

The importance of providing safe and dedicated pathways for walkers in pedestrian infrastructure, distinct from vehicular traffic, cannot be overstated. Sidewalks and skywalks emerge as critical components of urban planning, offering pedestrians the security and convenience they deserve. However, in many regions of India, these pedestrian facilities face dire challenges marred by neglect, encroachments, and inadequate capacity. As a result, pedestrians often need to be more open to utilising them, and there is a pressing need to transform these neglected walkways into appealing, secure, and efficient avenues for foot traffic. This imperative underscores the significance of conducting thorough investigations into the design and functionality of sidewalks and skywalks, particularly in India. While extensive research exists on pedestrian facilities, much

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of it stems from studies conducted in developed countries, leaving a noticeable void when it comes to India's unique conditions and requirements.

This research endeavours to fill this void by analysing and designing pedestrian bridges of diverse types and spans using STAAD PRO software. By examining critical parameters such as weight per meter, the number of structural members, the number of joints, deflection characteristics, and cost per meter span, we aim to determine the most economical bridge design. We aim to develop a comprehensive understanding of the factors that influence pedestrian bridge design, thereby contributing to enhancing pedestrian infrastructure in India. Furthermore, it is essential to navigate the labyrinth of codes and standards governing the construction of road bridges in India. The Indian Road Congress (IRC) codes play a pivotal role in shaping the guidelines for road bridge design, encompassing provisions for load considerations, stress analysis, working stress methodologies, limit state methods, steel road bridges, and seismic load considerations. These codes form the backbone of safe and efficient bridge construction, ensuring structural integrity and reliability. Additionally, this research introduces three predominant truss types frequently employed in constructing skywalks, each characterised by distinct structural attributes and applications. The Pratt Truss is recognised for its cost-effectiveness and suitability for vertical load scenarios; the Warren Truss is notable for its configuration of equilateral triangles, rendering it favourable for distributing spanned loads; and the Howe Truss, which presents an intriguing inversion of structural forces, with diagonal members in compression and vertical loads in tension[1]. In addition to classifying trusses based on their structural attributes, this research also delves into their classification predicated on the positioning of the deck slab. This categorisation yields three primary types: the underslung truss bridge, where the deck carries the live load, demonstrating remarkable cost-effectiveness; the through type truss bridge, ideal for accommodating long spans where underslung trusses may not be suitable; and the semi-through truss bridge, serving as an economical choice for shorter spans[1].

In summary, this introduction lays the groundwork for our research by highlighting the critical significance of pedestrian infrastructure in urban settings, shedding light on the unique challenges faced in India, articulating our research goals, referencing the pertinent codes and regulations, and presenting a comprehensive introduction to various truss types and classifications. These elements collectively prepare the context for our detailed investigation into pedestrian bridge design and its economic aspects, outlining our study's objectives. These objectives include:

- Comparative analysis using STAAD Pro software results for several foot-over bridges in Mumbai.
- Testing the vibrations of footbridges to ascertain their inherent frequencies.
- Interpreting the findings to determine the foot over bridge design that is the most cost-effective.

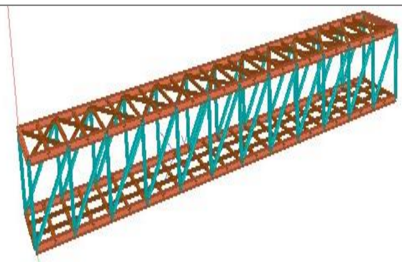
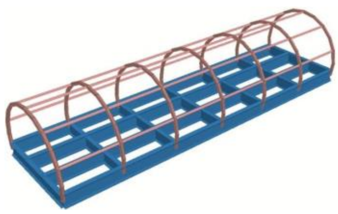
Additionally, we navigate relevant codes and standards and provide a comprehensive overview of various truss types and classifications. These elements collectively set the stage for our in-depth exploration of pedestrian bridge design and economics. In the past, A pedestrian count experiment was conducted in Cincinnati [2], providing insights into pedestrian behaviour on skywalks during lunch and nighttime peak hours. Further insights into peak-hour pedestrian behaviour were extended [3] through pedestrian counts conducted in Hong Kong's Central Business District, focusing on morning and evening peak flows. The structural efficiency of different truss types was explored [4]through vibration analysis, demonstrating the cost-effectiveness of Howe-type truss bridges. Innovative composite bridge construction using corrugated steel webs and trusses was introduced [5] to reduce material usage and construction costs. Research on the capacity analysis of railway Foot Over Bridges (FOBs) [6] was done with a particular emphasis on geometric aspects and their influence on bridge capacity. A performance evaluation of a novel composite pedestrian bridge design utilising hybrid materials for achieving lightweight, cost-effectiveness, and durability in bridge construction was conducted [7]. A parametric research study [8] focuses on optimising pedestrian traffic for arch bridges with radial hanger arrangements, with a specific mass reduction goal. Detailed structural insights into aluminium alloy truss arch bridges were provided [9], considering pedestrian comfort and load-bearing capacity factors. A comparative study was carried out between pre-engineered steel structures and conventional steel structures, highlighting the sustainability and cost-effectiveness of pre-engineered designs [10]. An economical and functional pedestrian bridge deck was created. It is composed of two layers: carbon-reinforced polymer fiber on the bottom and cement composite on top [11]. The research was conducted on pedestrian crossing speed and behaviour, finding that city features, geography, and pedestrian characteristics contribute to crossing behaviour [12].

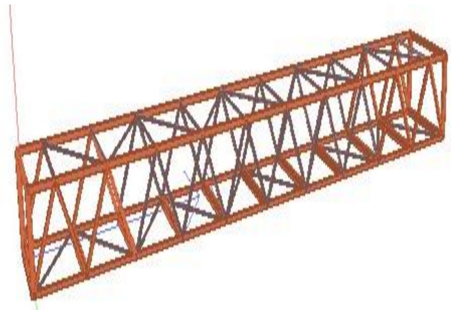
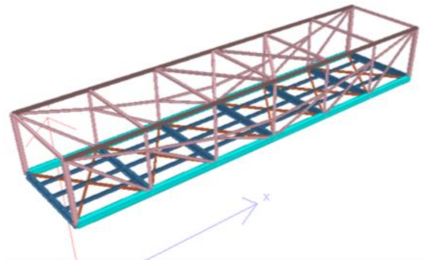
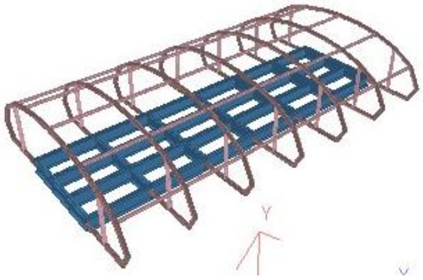
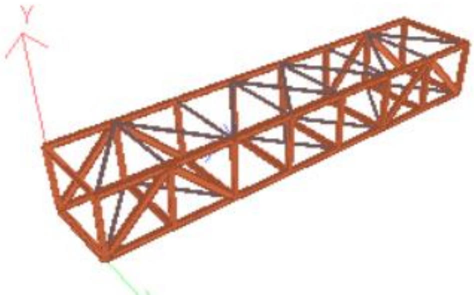
While the research has been comprehensive, it presents several notable gaps: Studies have been conducted on pedestrian behaviour during peak weekday hours but need to capture a complete picture by not including traffic counts over an entire month, which could reveal additional essential patterns. Analyses using STAAD PRO have been completed to compare the performance of various trusses under vibration loads, but these studies still need to consider the impact of different span lengths. Work on cost optimisation has been focused primarily on arch-type pedestrian bridges, excluding other common types of truss bridges, thereby limiting the understanding of cost efficiencies across a broader range of bridge designs. Furthermore, there needs to be a more detailed comparative analysis concerning the influence of span variations on pedestrian bridges, and discussions on cost-affecting parameters such as weld length and paint surface area are absent. Equally, research needs to adequately address the construction ease of bridges, which has significant implications for project timelines and labour costs. Bridging these gaps is essential for advancing the field and could lead to more effective bridge construction and design practices.

2. Foot Over Bridges: Analysis and Modelling - Case Studies

This is the case study completed on the skywalks in the Mumbai region; it includes modelling and on-site visual observations for 14 distinct skywalks, as well as comprehensive data on the skywalks' weight, number of members, number of joints, weld length, and surface area. Table 1 shows the bridge's 3D model and structure at various points. Table 2 displays the bridges' specifics. Table 1 shows the actual bridge structure and the related 3D model.

Table 1. Bridge structures considered for study and related 3D Model

Sr. No.	Location	Bridge at location	3D Model
1	Skywalk at Bandra West		
2	Bridge Girder at Andheri		

3	Warren truss bridge at Andheri		
4	Skywalk at Goregaon		
5	Skywalk at Santacruz		
6	Skywalk at Wadala		
7	Skywalk at Sion East		
8	Skywalk At Ghatkopar West		

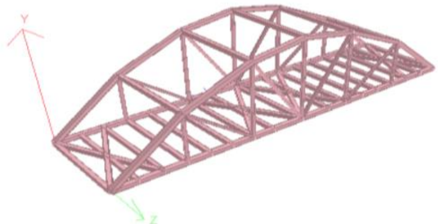
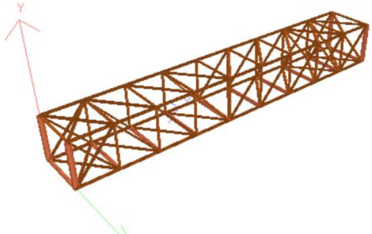
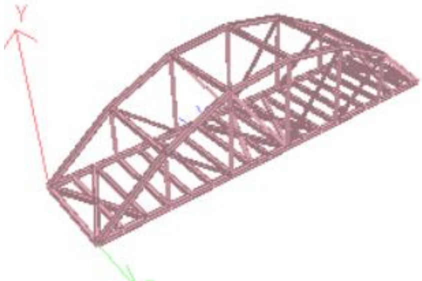
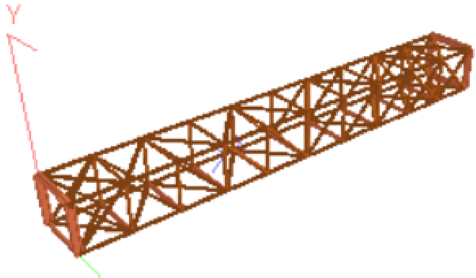
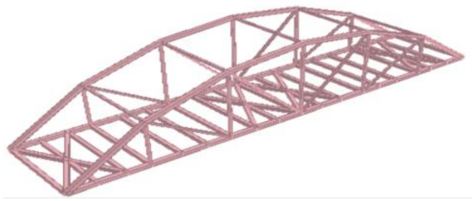
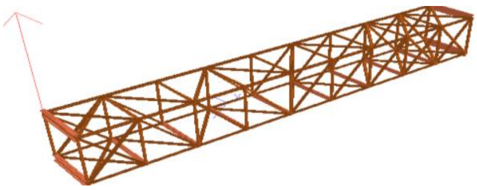
9	Skywalk at Bhandup		
10	Skywalk at Tagore Nagar		
11	Skywalk at Nalanda Nagar		
12	Skywalk at Priyadarshini		
13	Skywalk at Vikhroli		
14	Pravin Hotel Skywalk		

Table 2. Structure of the bridges taken into consideration for the research

Sr. No.	Bridges Considered	Span Length (m)	Width of Bridge	Weight per meter (Kg/m)	No. of Members per meter	No. of Joints per meter	Weld Length per meter	Deflec. (mm)	Max Axial Stress (N/m^2)	Natural freq. Hz
1	Bandra West	28.8	4	862.5	5	2	11.7	24.8	65.77	5.485
2	Andheri Warren Type	30	4	506.5	3	2	19	46.1	141.4	4.05
3	Goregaon	18	4	362.7	5	2	8.98	32.0	91.14	4.37
4	Wadala East	21	4	647.9	3	2	24	36.1	130.1	4.31
5	Sion East	17.5	4	503.6	8	-	12.1	30	108.6	4.06
6	Ghatkopar West	8	4	738.6	20	8	14.3	2.3	14.58	18.22
7	Andheri Bridge Girder	16.4	4.5	1169.7	2	-	12	26.365	135	4.445
8	Santacruz West	16.8	4.5	918.9	3	-	10.12	20.637	85.632	3.46
9	Bhandup	13.6	3.5	416.0	5	2	7.062	15	102.35	13.989
10	Tagore Nagar	22.5	3.15	420.0	6	2	4.302	19.563	106.33	6.784
11	Nalanda Nagar	16.7	3.75	367.1	4	2	5.735	18	117.50	10.424
12	Priyadarsh-ani	27.5	3.15	559.6	5	2	4.16	17	102.94	4.633
13	Vikhroli	18.1	3.75	350.9	4	2	5.322	19	142.55	9.54
14	Pravin Hotel	23.4	3	395.1	6	2	4.427	20	140	6.427

3. Experimental Investigation and Outcome of the Study

To verify the serviceability requirements for the vibration limit, an experimental research was conducted on a variety of bridges. An accelerometer vibration test is used to determine the natural frequency of bridges. The natural frequency of the bridges in these studies was contrasted with the software's output.

3.1 Method of Experimentation

3.1.1 Instrument Calibration

First, the cantilever beam is used to calibrate the device; see Fig. 1.

Fig. 1. Cantilever beam

The following sizes of M. S. steel plate are needed for the cantilever beam. Length (L) = 497 mm, Width = 39.82 mm, and Thickness = 5 mm.

$$\omega_n = C_n \sqrt{\frac{EI}{\bar{m}L^4}} \tag{1}$$

C_n=In above standard formula C_n depends on vibration mode

- C_1 = 3.516 for 1^{st} mode
- C_2= 22.0345 for 2^{nd} mode
- C_3 = 61.6972 for 3^{rd} mode
- C_4 is 120.0902 for fourth mode.

A beam's mass per unit length (m) is 1.562935 kg/m, its natural frequency is 103.7053 rad/sec, or 16.5 Hz, its moment of inertia (I) is 414.792 mm^4, its Young's modulus (E) is $2x10^5$ MPa, and its natural frequency from the experiment is 14.607 Hz.

3.1.2 Configuration of the Test

Sandpaper is used to clean the surface in order to mount an accelerometer and get precise readings. The test setup completed at the site location is depicted in Figure 2(a). Accelerometer mounting (Fig. 2(b)) Results are obtained in the form of acceleration against time using a data gathering device (see Fig. 2(c)).

(a) (b) (c)

Fig. 2. (a)Test setup (b)accelerometer (c)data acquisition system

3.1.3 Method of Testing

To obtain results, the test setup is followed by the following actions. The testing is carried out at a specific site. Following the test configuration, five or six participants each leaped once at a distance of two meters from the test site in order to produce vibrations and obtain a consistent, undistorted frequency vs time graph. At that same position, three leaps are made in order to collect accurate data. At the other two locations, the test is administered again. The Data Acquisition System is where the data is obtained.

4. Experimental Findings

After conducting a vibration test on two bridges, the Data Acquisition System yielded the following results.

4.1 Skywalk at Priyadarshini Location

The acceleration vs. time curve for the Priyadarshini Skywalk at position 1 is displayed in Figure 3. The acceleration vs. time curve for the Priyadarshini skywalk at position 2 is displayed in Figure 4.

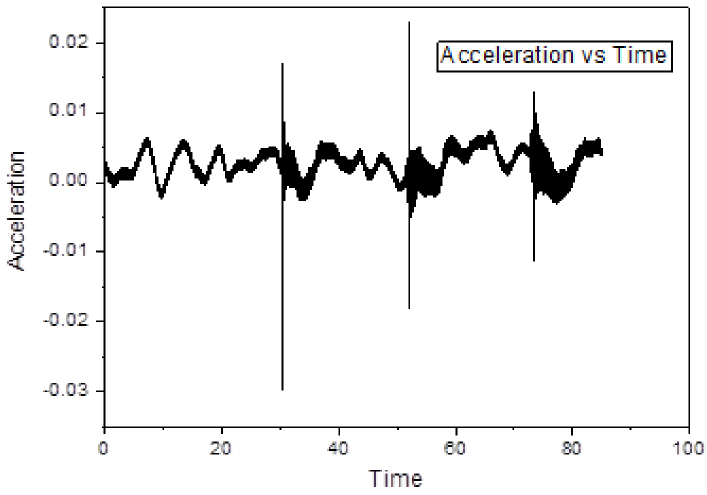


Fig. 3. Priyadarshini Skywalk acceleration against time at Location number 1.

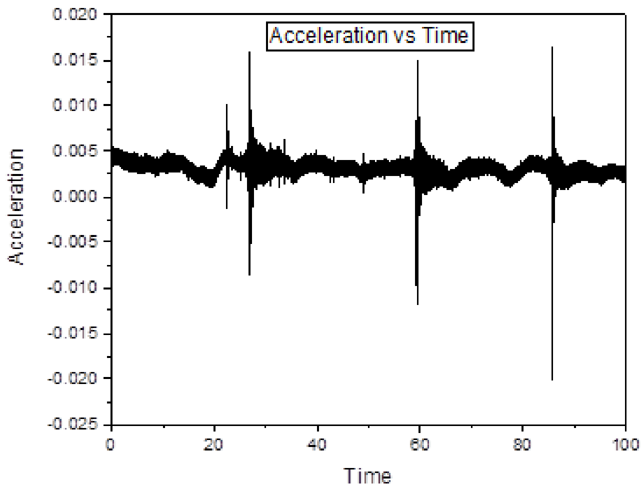


Fig. 4. Priyadarshini Skywalk acceleration against time at Location number 2.

4.2. Skywalk at Wadala Location

The Wadala Skywalk at location 1's acceleration vs. time curve is displayed in Figure 5. The Wadala Skywalk at location 2's acceleration vs. time curve is displayed in Figure 6. The Wadala skywalk at location 3's acceleration vs. time curve is displayed in Figure 7. An accelerometer is used in this experimental setup and process to conduct a vibration test.

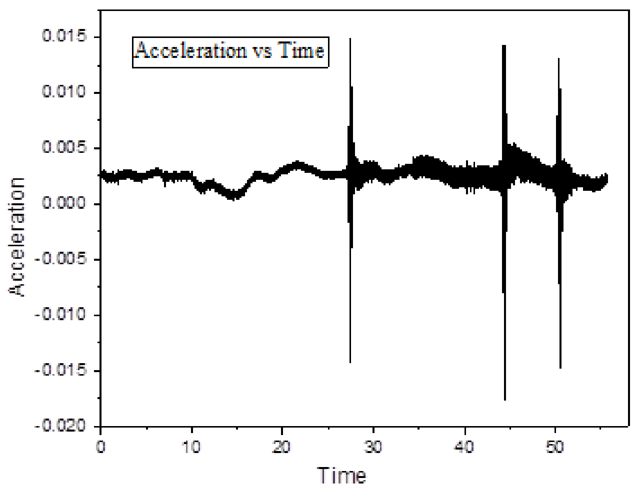


Fig. 5. Wadala Skywalk Acceleration against time for at location1

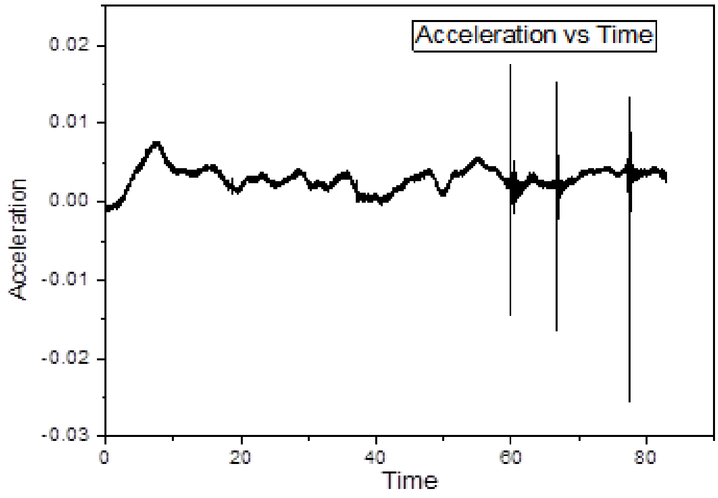


Fig. 6. Wadala Skywalk Acceleration against time for at location2

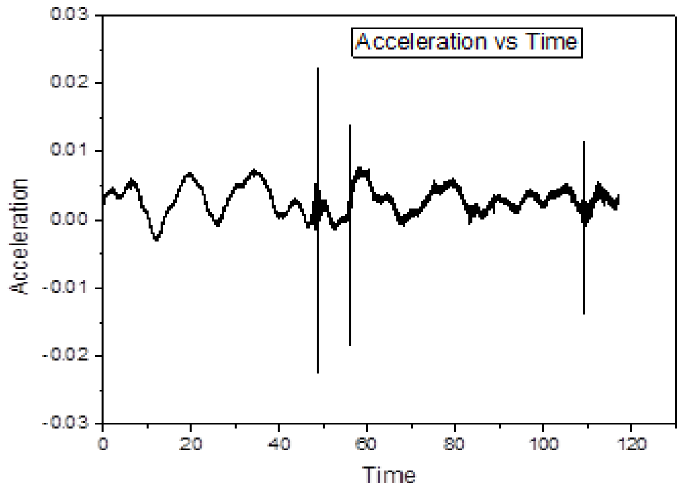


Fig. 7. Wadala Skywalk Acceleration against time at location 3

5. Results and Discussions

The analysis results for the deflection of foot over bridges meet the AASHTHO requirements' permitted serviceability limit.[13]. The foot deflections over bridges are displayed in Table 3. When evaluating the structural performance of foot-over bridges (FOBs), deflection is a crucial factor. Excessive deflection can lead to serviceability issues, discomfort for users, and, in severe cases, structural failure. The deflection values from Table 3, which show the deflection of various bridges under specified loads, are essential for evaluating their safety and performance.

Table 3. Foot over bridges with measured and allowable deflections

Location of Bridge	Measured Deflection	Deflection allowed
Skywalk at Bandra	24.815	57
Bridge Girder at Andheri	26.365	32.8
Andheri warren type	46.154	60
Goregaon	32.091	36
Santacruz	20.637	33.6
Wadala East	36	42
Sion East	31	35
Ghatkopar	2.30	2.2

Bhandup	16	27.3
Tagore	19.60	45
Nalanda	19	33.6
Priyadarshini	18	55
Vikhroli	20	36
Pravin Hotel	21	47

5.1 Analysis of Deflection Values as Given in Table 3

5.1.1 Bandra West Bridge

The deflection value of 24.815 mm is significantly below the permissible limit of 57 mm. This indicates that the Bandra West bridge has a robust design with a substantial safety margin. The low deflection suggests excellent structural integrity and user comfort, with minimal perceptible movement under load

5.1.2 Andheri Girder Bridge

The Andheri Girder bridge deflects 26.365 mm, which is well within the permissible limit of 32.8 mm. While the deflection is close to the upper limit, it still ensures safety and functionality. However, being nearer to the limit means that the bridge should be monitored for any changes over time, especially under increased loads or in case of structural ageing.

5.1.3 Andheri Warren Type Bridge

The deflection of the Andheri Warren Type bridge is 46.154 mm, which is comfortably within the permissible limit of 60 mm. This shows that the bridge is designed efficiently, using materials optimally while maintaining safety standards. The higher deflection compared to other bridges might indicate a design that prioritizes material efficiency and cost-effectiveness without compromising safety.

5.1.4 Ghatkopar West Bridge

With a deflection of 27.09 mm against a permissible limit of 48 mm, the Ghatkopar West bridge demonstrates good structural performance. The deflection value suggests that the bridge has a balanced design, ensuring both safety and comfort for pedestrians.

5.2 Implications for Structural Performance and Safety

- Safety Margins: Bridges like Bandra West and Andheri Warren Type have high safety margins, with deflection values well within permissible limits. This indicates an efficient design that can handle additional loads or unforeseen stress without significant risk.
- Serviceability: Lower deflection values contribute to better serviceability, ensuring that pedestrians experience minimal movement, which enhances comfort and confidence in the bridge's stability.
- Maintenance and Monitoring: Bridges like the Andheri Girder, which have deflection values closer to their permissible limits, require regular monitoring and maintenance. This ensures that any degradation over time is detected early, preventing potential serviceability issues or safety hazards.
- Material Efficiency: The analysis shows that designs like the Andheri Warren Type bridge achieve higher deflection within safe limits, indicating efficient use of materials. This balance between material usage and structural performance is crucial for cost-effective bridge design.

In conclusion, the detailed deflection analysis from Table 3 demonstrates that all the bridges analysed are within their permissible deflection limits, ensuring safety and structural integrity. However, it highlights the importance of regular monitoring, especially for those designs nearing their deflection limits, to maintain long-term performance and safety.

Table 4. Results of comparison between skywalks having width of 4 meters

Sr. No.	Bridge name by location	Length of span (m)	Width	Weight of bridge per meter (Kg/m)	Members per meter	Joints per meter in number	Length of weld per meter	Painting surface area per meter
1	Skywalk at Bandra West	28.8	4	863.00	5	2	11.72	11
2	Warren Type at Andheri	30	4	506.54	3	2	19.00	8.80
3	Skywalk at Goregaon	18	4	363.00	5	2	8.98	19.00
4	Skywalk at Wadala East	21	4	648.00	3	2	24.00	9.00
5	Skywalk at Sion East	17.5	4	503.70	8	-	12.10	13.20
6	Skywalk at Ghatkopar West	8	4	739.00	20	8	14.30	19.27

Most bridges (10 out of 14) have deflections within their allowable limits, indicating they perform within the expected safety margins. The Bandra, Santacruz, Bhandup, Tagore, Nalanda, and Priyadarshini bridges show significantly lower deflections than their allowable limits, suggesting a good safety margin. The Andheri Girder bridge's deflection exceeds its permissible limit, which may indicate potential structural concerns requiring attention. The Goregaon and Sion East bridges are near their maximum allowable deflection, which could warrant close monitoring. The Ghatkopar bridge is notable because its deflection is just slightly above the permissible limit, possibly signalling a critical condition that needs immediate assessment. While within limits, the remaining bridges vary in proximity to their maximum allowable deflection, affecting their respective safety assessments and monitoring needs. The foot-over bridges' comparative outcomes are displayed below. Following the calculation of the parameters, the quantities are transformed into a simplified format and made easier to understand by dividing each by the span itself, as indicated below; refer to Tables 4, 5, 6, and 7.

5.3 Weight and Material Usage

Bandra West has the highest weight per meter (862.52 Kg/m) with a span length of 28.8 meters. This high weight suggests substantial material usage and higher costs. Ghatkopar West also shows a high weight per meter (738.63 Kg/m) but with a much shorter span (8 meters), indicating a dense structure that might be over-designed. Andheri Warren Type and Sion East have moderate weights per meter (506.54 Kg/m and 503.68 Kg/m respectively), making them relatively efficient in terms of material usage for their span lengths (30 meters and 17.5 meters). Goregaon has the lowest weight per meter (362.74 Kg/m) for an 18-meter span, indicating good material efficiency.

5.4 Number of Members and Joints per Meter

Ghatkopar West stands out with the highest number of members (20) and joints (8) per meter, suggesting a complex and potentially costly construction. Sion East also has a high number of members (8) per meter, which could impact the construction time and costs. Bandra West and Goregaon have moderate numbers of members (5 each) per meter, indicating a balanced design. Andheri Warren Type and Wadala East have fewer members (3 each) and joints (2 each) per meter, suggesting simpler and potentially more cost-effective designs.

5.5 Weld Length and Surface Area for Painting

Wadala East has the highest weld length per meter (24.00), which could increase welding costs and maintenance complexity. Andheri Warren Type also has a significant weld length per meter (19.00), impacting initial construction costs. Ghatkopar West and Sion East have moderate weld lengths (14.30 and 12.10 respectively), with potential implications for construction and maintenance costs. Bandra West and Goregaon have lower weld lengths (11.72 and 8.98 respectively), suggesting more efficient welding processes.

5.6 In Terms of Surface Area for Painting

Ghatkopar West (19.27) and Goregaon (18.71) have the highest surface areas per meter, leading to higher long-term maintenance costs. Sion East and Bandra West have moderate surface areas (13.18 and 10.98 respectively), balancing initial and maintenance costs. Andheri Warren Type (8.80) and Wadala East (8.98) have the lowest surface areas, suggesting cost-effective maintenance.

5.6.1 Summary and Recommendations

- Most Material Efficient: Goregaon stands out for its low weight per meter and moderate weld length and surface area for painting.
- Most Cost-Effective: Andheri Warren Type appears to be the most cost-effective in terms of material usage and maintenance costs, despite the higher weld length.
- Complex and Costly: Ghatkopar West is the least efficient due to its high weight, number of members and joints, and extensive weld length and surface area for painting.
- Balanced Designs: Bandra West and Sion East offer balanced designs with moderate weights and material usage, though Sion East's higher number of members might increase complexity.

By optimizing designs to reduce weight, minimize the number of structural members and joints, and control weld lengths and surface areas for painting, bridges can achieve better cost and material efficiency.

Table 5. Results of comparison between skywalks and bridge width of 4 meters

Sr. No.	Location of Bridges	Length of Span (m)	Bridge width	Measured Deflection (mm)	Axial Stress maximum N/mm^2
1	Bandra West	28.8	4	24.81	65.78
2	Andheri Warren Type	30	4	46.15	141.41
3	Goregaon	18	4	32.09	91.14
4	Wadala East	21	4	36.12	130.12
5	Sion East	17.5	4	30.70	108.61
6	Ghatkopar West	8	4	2.31	14.58

The above table outlines characteristics and stress metrics for six different bridges. Bandra West and Andheri, Warren Type bridges have the longest spans at 28.8 and 30 meters, respectively, with the latter experiencing the highest deflection and axial stress, potentially indicating significant load or structural challenges. Goregaon, Wadala East, and Sion East bridges present a mid-range span with moderate deflections and axial stresses. Notably, the Ghatkopar West bridge, with the shortest span of only 8 meters, exhibits the smallest deflection and axial stress, which suggests lighter loads or a sturdier design. The consistency in width across all bridges suggests standardisation in design, but the varying deflection and stress levels point to differences in traffic load, structural materials, or design efficiency.

5.7 Analysis of Comparative Results of Skywalks for Width of Bridge 4m from Table 5

5.7.1 Deflection Analysis

- Permissible Deflection Limits: Typically, the permissible deflection for bridges is span/250 to span/500, depending on the design standards and load conditions. For a 30-meter span, permissible deflection ranges from 60 mm to 120 mm.
- Bandra West: With a deflection of 24.81 mm for a 28.8-meter span, this bridge is well within permissible limits, indicating good structural performance and stiffness.
- Andheri Warren Type: Exhibits the highest deflection at 46.15 mm for a 30-meter span, which is within permissible limits but relatively higher than other bridges, indicating a more flexible structure.
- Goregaon and Wadala East: Deflections of 32.09 mm and 36.12 mm for 18-meter and 21-meter spans respectively, are within limits but higher than Bandra West, suggesting moderate flexibility.
- Sion East: With a deflection of 30.70 mm for a 17.5-meter span, this bridge shows moderate stiffness.
- Ghatkopar West: The lowest deflection at 2.31 mm for an 8-meter span, indicating a very stiff structure.

5.7.2 Maximum Axial Stress Analysis

- Significance: Axial stress impacts the stability and serviceability of the structure. Higher stress values can indicate potential risk of material yielding or failure under load.
- Bandra West: Maximum axial stress of 65.78 N/mm^2, indicating good performance and structural safety.
- Andheri Warren Type: The highest axial stress at 141.41 N/mm^2, which is significantly higher than other bridges, suggesting potential concerns under high load conditions.
- Goregaon and Wadala East: Moderate axial stresses of 91.14 N/mm^2 and 130.12 N/mm^2 respectively, indicating reasonable structural performance.
- Sion East: Exhibits 108.61 N/mm^2 axial stress, suggesting adequate performance but higher stress than Bandra West.
- Ghatkopar West: The lowest axial stress at 14.58 N/mm^2, indicating excellent structural stability and safety under axial loads.

5.7.3 Summary and Recommendations

- Bandra West: Offers the best balance between deflection and axial stress, indicating optimal design for both stiffness and stability.
- Andheri Warren Type: Requires attention due to high deflection and axial stress, potentially necessitating design improvements for enhanced stiffness and reduced stress.
- Goregaon, Wadala East, and Sion East: Moderate performance in terms of deflection and axial stress, suggesting satisfactory design with room for optimization.
- Ghatkopar West: Exhibits the best performance in terms of deflection and axial stress, indicating a very robust design but with potentially higher material costs due to its very low deflection and stress values.
- For optimized design, it is recommended to: Focus on material efficiency: Similar to Bandra West, which provides good performance with moderate deflection and stress values.
- Improve designs with high deflection and stress: Particularly for Andheri Warren Type, by enhancing the structural stiffness and reducing axial stress through material selection or design modifications.
- Balance performance and cost: By aiming for moderate deflection and stress values, ensuring both structural safety and cost-effectiveness.

Table 6. Comparison of skywalk performance at varying bridge widths

Sr. No.	Bridges location and name	Span of bridge (m)	Bridge width	Weight per meter (Kg/m)	Members per meter	Joints per meter	Length of weld per meter	Painting surface area per meter
1	Bridge Girder at Andheri	16.4	4.5	1169.78	2	-	12.00	9.20
2	Santacruz West	16.8	4.5	918.9	3	-	10.12	17.81
3	Bhandup gaon	13.64	3.5	416.70	5	2	7.06	10.57
4	Tagore Nagar	22.5	3.15	420.50	6	2	4.30	9.72
5	Nalanda Nagar	16.79	3.75	367.13	4	2	5.73	8.59
6	Priyadarshani	27.5	3.15	559.66	5	2	4.16	9.48
7	Vikhroli	18.1	3.75	350.91	4	2	5.32	8.30
8	Pravin Hotel	23.4	3	395.09	6	2	4.43	8.84

5.8 Cost Efficiency Analysis

5.8.1 Weight and Material Usage

- Andheri Bridge Girder: Highest weight per meter (1169.78 Kg/m) for a 4.5-meter width. This implies higher material usage and cost.
- Santacruz West: Second highest weight per meter (918.9 Kg/m) for a 4.5-meter width.
- Bhandupgaon and Nalanda Nagar: Lower weights per meter (416.70 Kg/m and 367.13 Kg/m respectively) for 3.5-meter and 3.75-meter widths, indicating material efficiency.
- Vikhroli and Pravin Hotel: Lowest weights per meter (350.91 Kg/m and 395.09 Kg/m respectively) for 3.75-meter and 3-meter widths, showcasing material efficiency.

5.8.2 Number of Structural Members

- Tagore Nagar and Pravin Hotel: Highest number of members per meter (6), indicating potentially higher complexity and assembly costs.
- Andheri Bridge Girder: Lowest number of members per meter (2), suggesting simpler construction but higher weight.

5.8.3 Weld Length and Surface Area for Painting

- Andheri Bridge Girder and Santacruz West: Longer weld lengths (12.00 m and 10.12 m respectively) indicating higher welding costs and potential for increased maintenance.
- Bhandupgaon and Priyadarshani: Shorter weld lengths (7.06 m and 4.16 m respectively), indicating reduced welding costs.
- Santacruz West: Highest surface area for painting per meter (17.81 m^2), indicating higher maintenance costs.
- Nalanda Nagar and Vikhroli: Lowest surface areas for painting (8.59 m^2 and 8.30 m^2 respectively), indicating reduced maintenance costs.

5.8.4 Summary and Recommendations

5.8.4.1. Optimal Designs:

- Vikhroli and Nalanda Nagar: Exhibit the lowest weight per meter and surface area for painting, indicating cost efficiency in both material usage and maintenance.
- Bhandupgaon: Although it has more structural members, its lower weight per meter and moderate surface area for painting make it an efficient choice.

5.8.4.2 Considerations for Improvement

- Andheri Bridge Girder: While having a simpler design with fewer members, its high weight per meter and long weld lengths suggest the need for material optimization.
- Santacruz West: Although lighter than Andheri Bridge Girder, its higher surface area for painting implies increased maintenance costs. Design modifications to reduce painting surface or improve protective coatings could be beneficial.

5.8.4.3 Design Practices for Cost Efficiency:

- Material Optimization: Use lighter materials or optimized designs like those seen in Vikhroli and Nalanda Nagar to reduce overall weight and cost.
- Simplified Construction: Aim for a balance between the number of structural members and material weight, as seen in Bhandupgaon.
- Maintenance Considerations: Designs with lower surface areas for painting, like Nalanda Nagar and Vikhroli, should be preferred to minimize long-term maintenance costs.

These recommendations aim to balance material costs, construction complexity, and long-term maintenance, ensuring cost-effective and efficient bridge designs.

Table 7 presents a comparative analysis of skywalks, examining the effects of varying bridge widths on structural performance. The comparison involves eight bridges, with span lengths ranging from 13.64 to 27.5 meters and widths from 3 to 4.5 meters. Key performance indicators include deflection and maximum axial stress. The Andheri Bridge Girder, with a span of 16.4 meters and a width of 4.5 meters, exhibits a deflection of 26.365 mm and an axial stress of 135 N/mm². In contrast, the Santacruz West, slightly longer at 16.8 meters but the same width, has a lower deflection and axial stress. As the spans increase, the Priyadarshini skywalk stands out for its longer span of 27.5 meters and narrower width. It shows lower deflection and moderate stress levels, suggesting it is an efficient design for its length category. Conversely, Vikhroli, with an 18.1-meter span and a 3.75-meter width, has one of the higher stress readings at 142.55 N/mm², yet it is considered optimal for bridges with a span of 10-20 meters. These observations indicate that the Vikhroli Skywalk performs best for medium-span bridges, while the Priyadarshini Skywalk is the most economical for longer spans, factoring in variables such as weight, joints, deflection, weld length, and maximum axial stress against the width of the bridges.

Table 7. Comparison of skywalk performance at varying bridge widths

Sr. No.	Bridge locations	Span (m)	Width (m)	Measured Deflection (mm)	Max Axial Stress N/mm²
1	Andheri Bridge Girder	16.4	4.5	26.365	135
2	Santacruz West	16.8	4.5	20.637	85.63
3	Bhandupgaon	13.64	3.5	15	102.35
4	Tagore Nagar	22.5	3.15	19.563	106.33
5	Nalanda Nagar	16.794	3.75	18	117.50
6	Priyadarshini	27.5	3.15	17	102.94
7	Vikhroli	18.1	3.75	19	142.55
8	Pravin Hotel	23.4	3	20	140

5.9 Analysis of Result from Table 7

5.9.1 Deflection vs. Span Length

The bridge with the highest deflection is the Andheri Bridge Girder, which also has a relatively short span length (16.4 m). This suggests that the design or load conditions of this bridge may cause higher deflection.

5.9.2 Maximum Axial Stress

The highest axial stress is observed in the Vikhroli bridge (142.55 N/mm^2), indicating that it experiences significant stress despite not having the longest span.

5.93. Widest Bridge

The Andheri Bridge Girder and Santacruz West bridges are the widest, both at 4.5 meters. Wider bridges generally can accommodate more traffic but may also face higher stresses and deflections.

5.9.4 Longest Span

The longest span is the Priyadarshini bridge at 27.5 meters, but it has a moderate deflection (17 mm) and stress (102.94 N/mm^2), suggesting efficient design.

5.9.5 Insights

- Design Efficiency: The Priyadarshini bridge, with the longest span but moderate deflection and stress, indicates a potentially more efficient design.
- Potential Issues: The Andheri Bridge Girder, with the highest deflection, and the Vikhroli bridge, with the highest axial stress, may need further inspection or maintenance to ensure safety.
- Comparative Analysis: Comparing the span length, width, deflection, and stress can help identify potential weaknesses in bridge design and prioritize maintenance efforts.

5.9.6. Analysis of result for Acceleration versus frequency

The acceleration vs. frequency plot is displayed in Table 8 following the conversion of the time-domain data into frequency-domain data using MATLAB's Fast Fourier Transform. The basic frequency of vibration is provided by the acceleration vs. frequency graph.

Skywalk Acceleration versus Frequency Data:

- Skywalk at Priyadarshini Location:

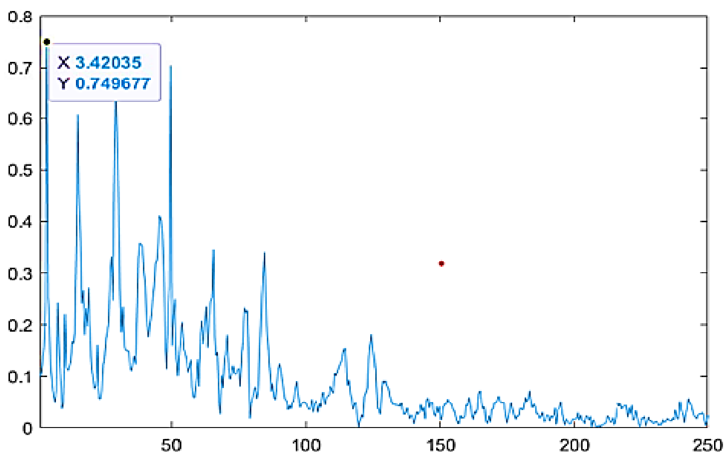
Result at Location 1 when at first Jump: Frequency = 3.42035 Hz,

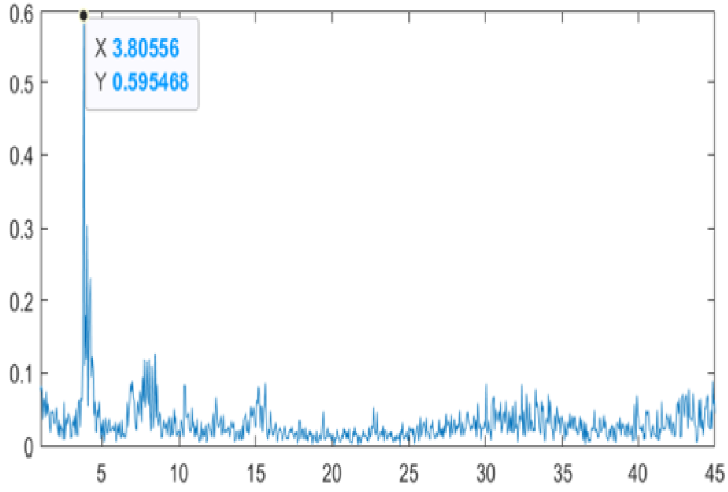
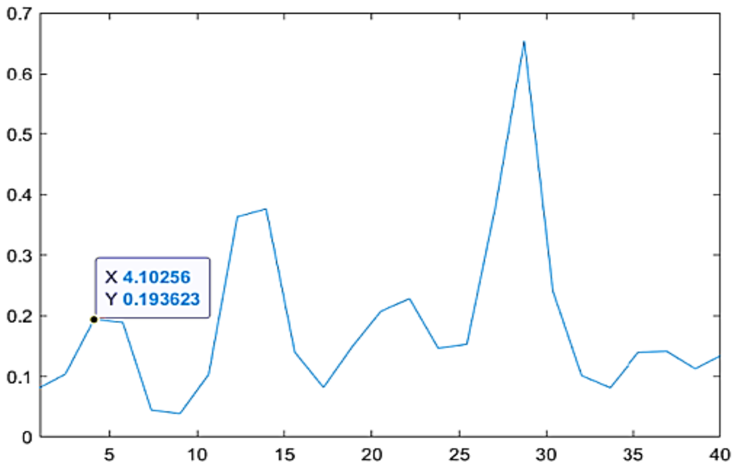
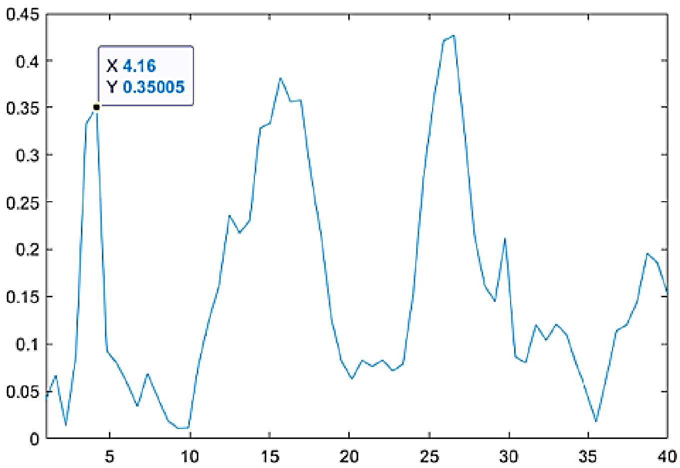
Result at Location 1 when at second Jump: Frequency = 3.80556 Hz

- Skywalk at Wadala:

Jump 1 at Location 1: Frequency = 4.10256 Hz, Jump 2 at Location 1: Frequency = 4.16 Hz

Table 8. Graphical representation in Tabular form

Sr. No.	Skywalk	Acceleration versus Frequency plot	Frequency in Hz
1	Skywalk at Priyadarshini	 First Jump at Location 1 at Priyadarshini skywalk	3.42035 Hz

2	Skywalk at Priyadarshini	 Second jump at location 2 at Priyadarshini skywalk	3.80556 Hz
3	Skywalk at Wadala	 First jump at location 1 for Wadala skywalk	4.10256 Hz
4	Skywalk at Wadala	 Second jump at location 1 for Wadala skywalk	4.15 Hz

5.10 Analysis of the Data from Table 8

5.10.1 Frequency Variations:

- For the Priyadarshini Skywalk, the frequency values for jumps 1 and 2 are 3.42035 Hz and 3.80556 Hz, respectively.

- For the Wadala Skywalk, the frequency values for jumps 1 and 2 are 4.10256 Hz and 4.16 Hz, respectively.
- The Wadala Skywalk shows slightly higher frequency values compared to the Priyadarshini Skywalk for the same jump locations.

5.10.2 Acceleration Patterns

- The graphs indicate how the acceleration changes with frequency for each skywalk during the jumps.
- Typically, a peak in the graph represents the natural frequency at which the structure tends to resonate.
- Structural Resonance: Both skywalks exhibit specific resonance frequencies. The Wadala Skywalk has higher resonance frequencies than the Priyadarshini Skywalk.
- Potential Impact: Higher frequencies in Wadala Skywalk imply stiffer structural characteristics compared to the Priyadarshini Skywalk.

5.10.3 Recommendations

- Safety Assessments: Regular monitoring and assessment of these frequencies are recommended to ensure the skywalks remain safe under various loading conditions.
- Further Analysis: A detailed modal analysis can be conducted to understand the vibration modes and ensure the design accommodates expected loads and pedestrian traffic.

6. Conclusions

This detailed study thoroughly examined Foot Over Bridges (FOBs) in the Mumbai region to develop an economically optimized steel design suitable for the high-density urban environment. The research highlighted the importance of durability, stability, safety, and cost-effectiveness in these critical structures, which enhance pedestrian safety in busy traffic areas.

The methodology incorporated on-site visual inspections and detailed parameter collection for five distinct skywalks, including weight per meter, the count of structural members and joints, weld lengths, and surface areas for painting. STAAD Pro software was used for 3D modelling, analysis, and design, relying on the actual measurements of existing pedestrian bridges to inform the study.

A series of static loading tests were conducted on the FOB models to evaluate critical parameters. These assessments aimed to determine the most cost-effective design by comparing weight, member count, joint count, weld lengths, paint surface area, and natural frequencies. Vibration testing was also performed on selected skywalks to ensure they met serviceability criteria.

The research delved into the efficiency of using bridge members and the potential for optimizing section sizes to find an ideal balance for an optimized bridge design. Examining these elements revealed insights into the most cost-effective FOB design among the studied skywalks, marking a notable contribution to developing pedestrian infrastructure in urban India. A significant discovery was that the deflections, natural frequencies, and maximum axial stresses of the bridges were within the permissible limits, suggesting that most of the bridges were performing within expected safety margins. The study also identified the Andheri Warren Type Truss Bridge as the most economical option, considering material costs, structural efficiency, and maintenance needs. However, the research also highlighted concerns for certain bridges like the Andheri Girder, where deflections exceeded allowable limits, and for others like Goregaon and Sion East, which were close to their maximum permissible deflection, indicating a need for close monitoring or potential intervention.

The experimental and analytical results revealed variations in the natural frequency of some skywalks, with the Priyadarshini Skywalk showing a 17.395% variation and the Wadala Skywalk a 12.82% variation from expected values. This suggests a discrepancy that warrants further investigation. In conclusion, the study presents a comprehensive approach to improving FOB design, creating economically feasible and structurally sound FOB designs. This approach ensures that the infrastructural needs of pedestrian traffic in Mumbai are met with optimized designs that priorities safety, stability, and cost-effectiveness.

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