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# Static and Eigenvalues Analyses of Steel-Truss Type Footbridges of Arched Deck

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***Abstract* - In the present study, three dimensional static and eigenvalues analyses of steel-Warren truss footbridges of single (50m) span and arched deck have been performed. The analysis parameters are the deck camber (three cases), type of support (elastomeric pads or rigidly connected) and the truss (span/depth) ratio (23.8, 20.0, 16.6, 12.5 and 10.0). The maximum seasonal temperature change of $50^0$ c has also been considered. Accordingly, thirty bridge cases were analyzed. The maximum stress and the live load deflection were determined and from the eigenvalues analysis, the fundamental frequency was determined and compared with the limit stipulated in AASHTO specifications.**

**Results have indicated that bridges satisfying the stress and live load deflection limitations may not necessarily satisfy the minimum required fundamental frequency of (3HZ) as given in AASHTO specifications. Among all cases of arched deck-rigid ends bridges of the present study, the maximum reduction in stress was 51% and the maximum increase in the fundamental frequency was 114% as compared with flat deck bridges supported on elastomeric pads. It was concluded that for any other footbridge type, a parametric study is needed to find the required bridge properties and the most suitable geometry to achieve the serviceability limit state.**

*Keywords* - AASHTO specifications, Arched deck, Eigenvalues analysis.

## INTRODUCTION

Usually, steel footbridges are lighter and carry smaller live load as compared with vehicular bridges. Hence, they may be susceptible to excessive deflection and footsteps vibrations, and the serviceability requirements may not be achieved. Rigorous dynamic analysis is difficult to be made under footsteps dynamic load since this dynamic excitation is difficult to be estimated. It depends on many factors, such as the number of pedestrians crossing the bridge and their pacing and walking activities, Fig. (1). [1, 2, 3, and 4]. Due to these reasons most design standards rely on stipulating a minimum requirement for the fundamental natural frequency (as obtained from eigenvalues analysis) in lieu of the time domain dynamic analysis, [5,6].

FIG. 1
FOOTSTEPS ON FOOTBRIDGES

To increase the fundamental frequency, the global bridge stiffness can be increased. In conventional design, this may usually be achieved by enlarging the section of members, using intermediate supports, and/or reducing the (span/ depth) ratio. In addition, the bridge global stiffness may be increased by changing its geometry, for instance, arch bridge models may be adopted.

## PREVIOUS STUDIES AND CODES OF PRACTICE

The footsteps vibration discomfort can be mitigated by specifying a minimum limit for the fundamental frequency, [7]. A review of some previous studies about minimizing the vibration discomfort can be found in references [2, 3]. The AISC [7] stipulated a minimum required fundamental frequency for floors rather than for footbridges. Arch bridges serviceability study was implemented and limiting the bridge frequency was the major conclusion to mitigate the annoying feeling of footsteps vibration [8]. Table (1) summarizes the live load deflection and natural fundamental frequency limits according to BS5400 [6] and AASHTO [5].

TABLE 1
LIVE LOAD DEFLECTION & NATURAL FUNDAMENTAL FREQUENCY LIMITS

| | Bs5400, pt.2 [6] | AASHTO,[5] |
|---|---|---|
| Pedestrian Load $(\frac{KN}{m^2})$ | $W_L = 5.0\,(\frac{151(1/L)^{0.475}}{30})$<br>L= span (m)<br>$W_l$=live load (KN/m$^2$) | 4.20 |
| Live load deflection limit $\delta_L$ | $\delta_L \leq L/360$ | $\delta_L \leq L/360$ |
| Fundamental frequency limit $f_1$ (Vertical) | $f_1 \geq 5\ HZ$<br>If $f_1 < 5HZ$ :<br>The max. acceleration is to be determined & $\leq 0.5\sqrt{f1}$ (m/$s^2$) | $f_1 \geq 3HZ$ *and* $\geq 2.86\ \ln(\frac{180}{W})$<br>W=Bridge self-weight. (Kips) |

At the time of preparing this study, no previous related research had been traced in the literature survey about the control of footsteps vibration for arched deck footbridges. In addition, no code of practice had given an acceptable range for the deck radius of curvature for footbridges. However, as cited in reference [9] the maximum gradient range for pedestrian ramps is given, Table (2). Practically, the deck curvature may be estimated on the basis of maximum comfortable ramp gradient.

TABLE 2
MIN. WIDTH AND MAX. RAMP GRADIENT FOR PEDESTRIAN BRIDEGES[9]

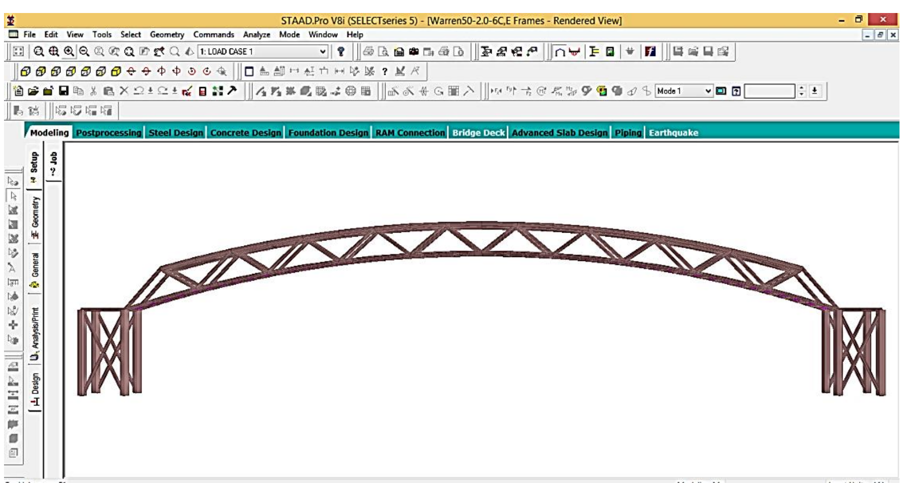
| Standard | Country | Min. path Width (m) | Max. gradient [%] |
|---|---|---|---|
| Austroads | Australia | 1.5-1.8 (pedestrians)<br>1.5-3.0 (cyclists)<br>2.5-3.0 (mixed) | 12.5 (pedestrians)<br>5.0 (cyclists)<br>3.0 (mixed) |
| Structure design manual | Hong Kong | 2.0 (pedestrians)<br>3.0 (in metro stations) | 5.0–8.3 (pedestrians)<br>4.0-8.0 (cyclists) |
| Japanese footbridge Design code (1979) | Japan | 3.0 (pedestrians) | 5.0 |
| British standard B8300 [10] | Great Britain | 1.8 (pedestrians)<br>2.0 (mixed)<br>2.7 (pedestrians)<br>2 (cyclist with seperate path ) | 5.0-8.3 (pedestrians) |

The minimum path width depends on bridge users (pedestrians, cyclists, or mixed), it is in the range of (1.5-3.0m).

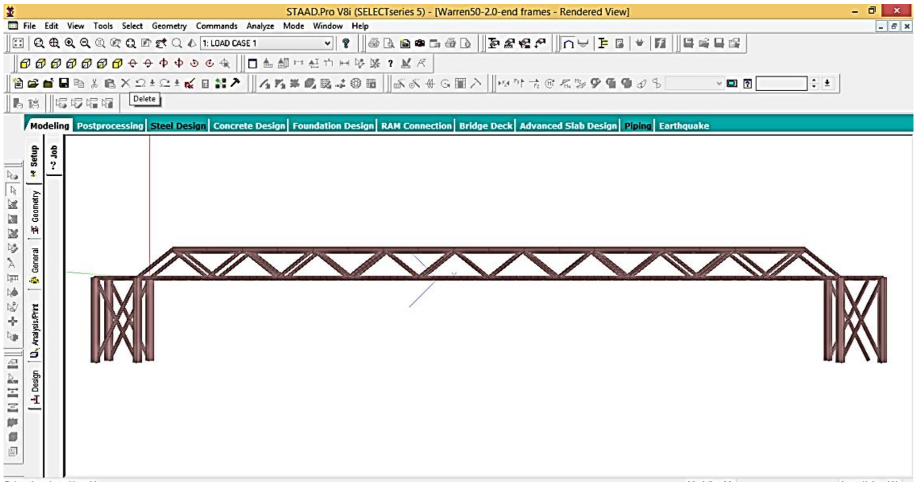
## APPLICATIONS

### *1. Bridge Geometry*

A 50 m single span steel-Warren truss footbridge has been analyzed in the present study. The bridge profiles are as shown in Fig (2).




(A)




(B)
FIG. 2
FOOTBRIDGE PROFILE

In Fig (2), the deck is either flat or has been arched as shown in Fig.(2a). As stated in sec. (2) no standard specification had specified a minimum limit for the radius of curvature for footbridge decks. However, in the present study acceptable deck radii of curvature have been estimated in view of the maximum allowable gradient of access ramps as assigned in some standards. Presumably, the deck camber ratio (H/0.5L) will, by analogy, be limited within the maximum gradient of accessible ramps. As given in Table (2). The maximum ramp gradients are 8.33% and 12.5% for the BS 8300 and for the Australian codes, respectively. These gradient limits are based on the perception of pedestrian comfort during walking. According to AASHTO [3] no maximum limits have been assigned for deck curvature and ramp gradients. Accordingly, the following mid span cambers and radii of curvature will be stipulated in the present study:

H1= 2.10m, for which R1=151m and H2=3.1m, for which R2=101m.

Based on the ranges of minimum bridge width given in Table (2) a 3.0 m path width will be adopted for this 50m bridge. The framing system of the bridge consists of two Warren trusses of various depths (2.10 – 5.0 m). The deck consists of parallel beams at 1.0 m c/c covered with a 6mm steel plate.

*2. Analysis Parameters and Properties of Members*

The analysis parameters considered in the present study are:-

- The deck curvature (Flat, 2.1 m and 3.1 m cambers).
- The supporting system (Elastomeric pads or rigidly connected ends)
- The effect of temperature ± 50 C̊
- The truss depth (2.1, 2.5, 3.0, 4.0, 5.0m)

This means that 30 bridge models have been analyzed under a live Load of 4.20 $KN/m^2$ as shown in Fig. (3), taken the following load combination into account:

Load case 1: (D.L+ L.L), Load case2: ΔT= +50 C̊, Load case3: ΔT= -50 C̊

Load combination 4: (case1 + case2), Load combination 5: (case1 + case3)

Load cases2 and 3 refer to the maximum seasonal temperature changes and taken as ± 50 C̊.

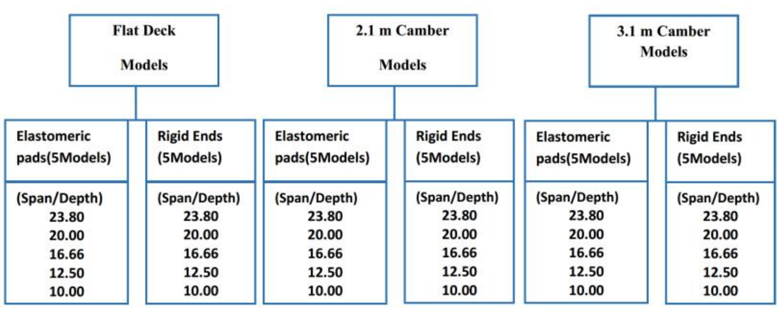


FIG. 3

Hypothetically, the consideration of temperature change effects is more essential when considering the bridge models of rigid ends (without using elastomeric pads). Four columns at each end of the bridge were adopted as shown in Fig (4). The use of the so called rigid ends arched deck (instead of elastomeric pads) will improve the adequacy of the bridge from the structural point of view.

To select the member properties many analyses have been made for the basic reference bridge of flat deck having a (2.1 m depth) so that the allowable steel stresses will not be exceeded (Assuming a yield strength of 350 MPa).

Staad Pro. V8i was used for this purpose. Results have shown that selecting the member proprieties shown in Fig.(4) results in maximum upper and lower chord stresses of 174 MPa (Comp.) and (123 Tension) respectively. These member properties were adopted for all other bridge cases of different analysis parameters.

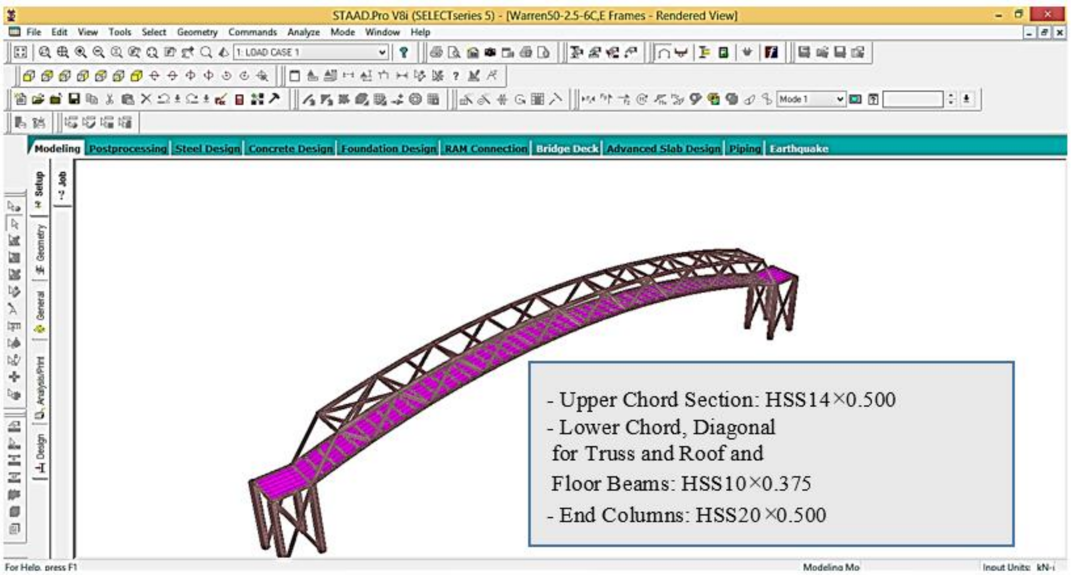



FIG. 4
FINITE ELEMENT IDEALIZATION AND MEMBER PROPERTIES

The elastomeric bearing pad dimensions used in this study have been selected based on AASHTO Standards [12]. The shear modulus (G) and the modulus of elasticity may be taken as 1.23 MPa and 600 MPa for rubber respectively.

The analysis results at each of the four supports are:-

$R_{TL} = Total\ dead\ and\ Live\ Loads\ reuction = 245\ KN$

$\Delta x = horizontal\ movement = 63mm\ (D.L + L.L + Temp.)$

$\theta s = support\ rotation = 0.0002\ rad.$

Considering a (25%) for 25 years creep deformation, hence:-

$\Delta x$ t =1.25*63=78.75mm

According to AASHTO [12]:

Total pad thickness > 2 $\Delta xt$ =157.5mm

Refering to any accepted elastomeric pads catalougue, for instance [13], a pad of dimensions 400*500*160 mm will be used for which :

H=160mm> 157.5 mm (required)

and $\theta$ max=0.022 rad.>> 0.002 rad

$Rtl$)max.=3000 KN >>245KN>>KN ( applied).

Total rubber thickness=115 mm.

This means that the horizontal deformation and consequently the pad thickness control the selection of pad dimensions.

The equivalent spring stiffenesses for the pad are :

Horizontal spring = $\frac{.G.A}{hr} = \frac{1.23*400*500}{115} = 2139N/mm$

Vertical spring = $\frac{E.A}{H} = \frac{600*400*500}{160} = 750000N/mm$

Rotaional spring $= \frac{E.I}{hr} = \frac{600*(400*500\frac{3}{12})}{115} = 21740\ kN.m/rad.$

These spring constants have been used at one end of the bridge and for the other end anchored type pads were used.

*3. Static and Eigenvalues Analyses*

Static analyses were performed for the 30 bridge models to obtain the maximum value for the live load deflection and the chord stresses under the load combinations stated in sec (3.2). Then a dynamic (eigenvalues) analyses were done under the self-weight for the bridge models to obtain the fundamental natural frequency majoring in vertical participation.

The AASHTO specification, [11] was followed for the serviceability requirements of footbridges, Table (1). The fundamental frequency should be ≥ 3HZ and in no case be smaller than 2.86 in $\frac{180}{W}$, where w is the bridge weight in (kips). This frequency limit had been decided according to this specification to keep it away

from the frequency range of walking (1.8-2.0 HZ), [9]. The maximum live load deflection should be ≤ span/360, Table (1). Fig.(5) shows a typical first mode shape of the 50m footbridge considered in the present study.

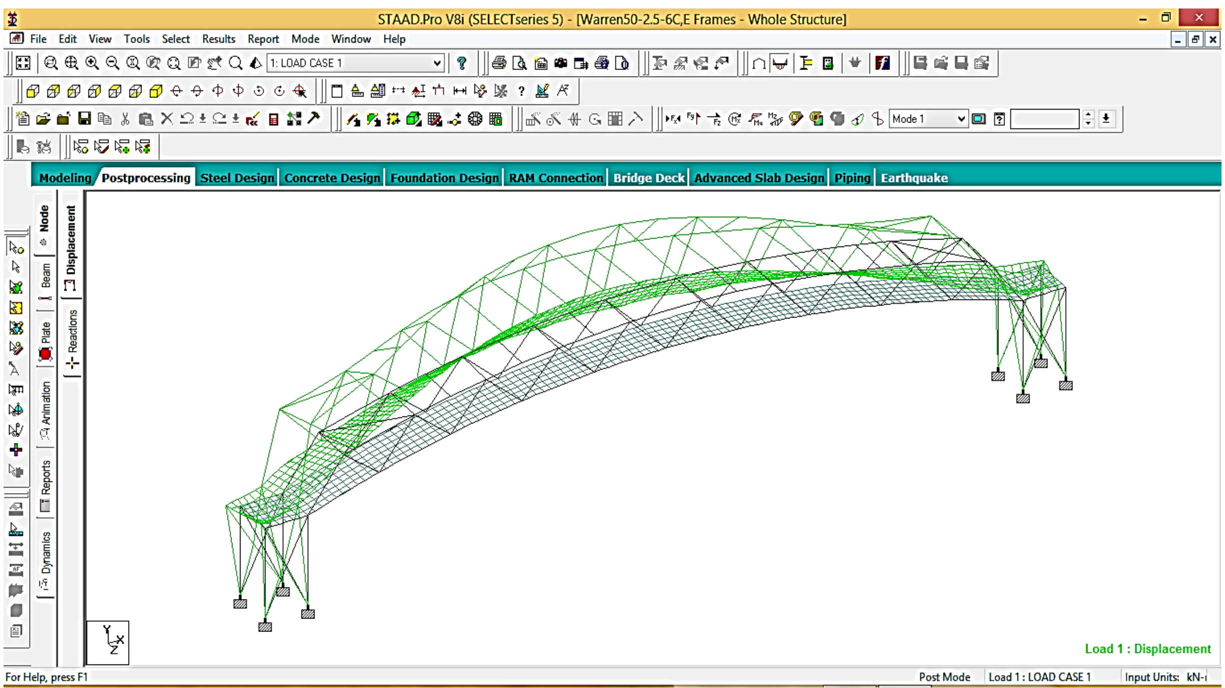



FIG. 5
TYPICAL FIRST MODE SHAPE OF VIBRATION

*4. Results Interpretation*

The analysis results are presented in Tables (3, 4, 5) and Figs. (6, 7, 8). The (span/depth) ratio has been used instead of the truss depth in results interpretation. The bridge analysis indicates that the flat deck bridge of depth 2.1m (23.8 span/depth /ratio) supported on elastomeric pads is deemed to be accepted with respect to the maximum stress (174MPa). According to AASHTO, [12] the allowable stress can be increased by a 1.25 factor when considering the temperature load combinations. Although this bridge model is satisfied with respect to the allowable stresses, its eigenvalues analysis indicates that its fundamental frequency is (2.27 HZ) which is less than the AASHTO, [5] minimum limit of (3.0HZ). Accordingly, the (span/depth) ratio, deck camber and the supports condition have been varied to trace the model that will simultaneously satisfy the frequency, stress, and live load deflection.

It is obvious from Table (3) and Fig. (8), that using the arched deck and /or rigid ends decreases the maximum upper chord stresses. The cases of flat deck bridges resting an elastomeric pad are considered the reference for comparison among other bridge cases. For rigid ends of 2.1m camber bridge, the stress reductions are 37%, 16%, 14%, 12 % and 4 % and the increase in fundamental frequencies are 55%, 40%, 33%, 28% and 20% respectively for (span/ depth) ratios of 23.8, 20.0,

16.6, 12.5 and 10.0.When the deck camber has been increased to 3.1m the stress reductions become 51%, 37%, 29%, 14% and 4% and the increase in fundamental frequency is 114%, 84%, 68%, 54% and 51% respectively.
Fig.(7), indicates that the deck camber increases the fundamental frequency effectively as compared among the other analysis parameters.

It is evident from Figs. (6, 8) that as the bridge becomes shallower (larger span/ depth) ratio, the effect of analysis parameters on the live load deflection and chord stresses becomes more pronounced.

Although all bridge models are accepted from the allowable stress point of view still the fundamental frequency and live load deflection limits should also be checked. For all models the live load deflection is less than (L/360=139 mm), Table (5). The fundamental frequency ranges from (2.27 HZ) to (7.31) HZ, Table (4). For all models, Table (4) indicates that when the (span/depth) ratio ≥ 16.66, the fundamental frequency is deemed to be satisfied (exceeding 3.0 HZ). For the design case of (span/ depth) ratio of 23.8 having rigid ends with a deck cambers of 2.1 m and 3.1 m the fundamental frequencies are (3.52 HZ) and (4.85 HZ) respectively. This leads to a conclusion that a 2.1 m deck camber of rigid ends bridge having 23.8 (span/depth) ratio is adequate statically and dynamically. Logically (in view of these results) the use of (span/ depth) ratio ≥ 16.66 is not justified. However if these deeper bridges are aesthetically required another analysis- design cycle is required to change member properties and to enhance the stress level.

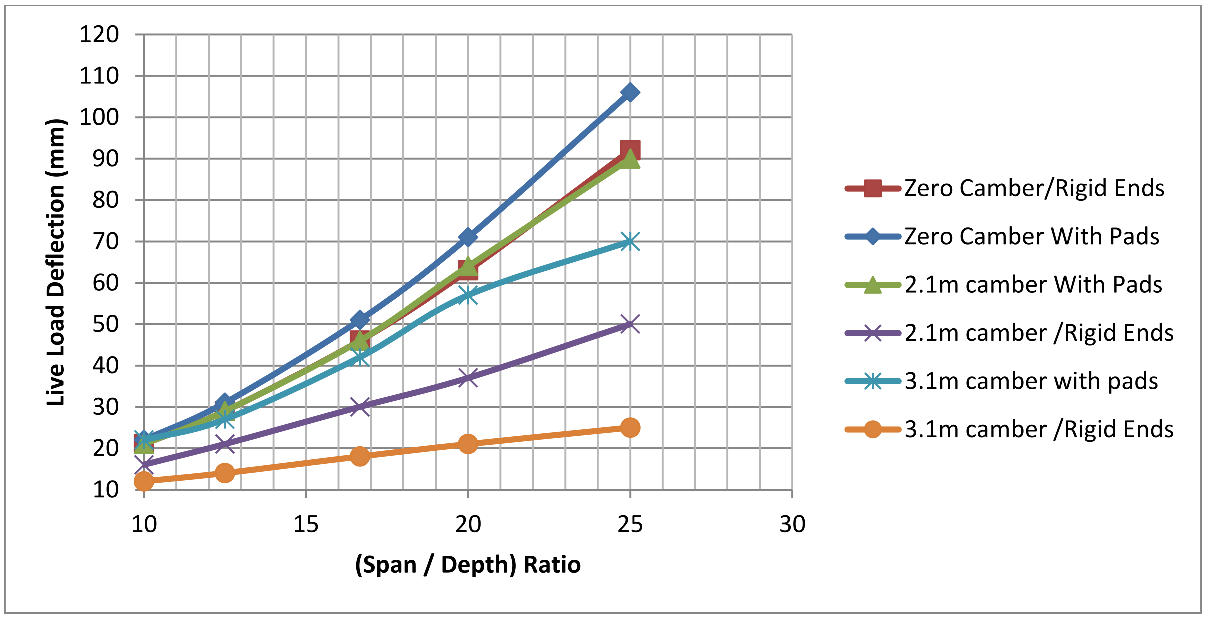



FIG. 6
LIVE LOAD DEFLECTIONS FOR DIFFERENT BRIDGE DEPTHS

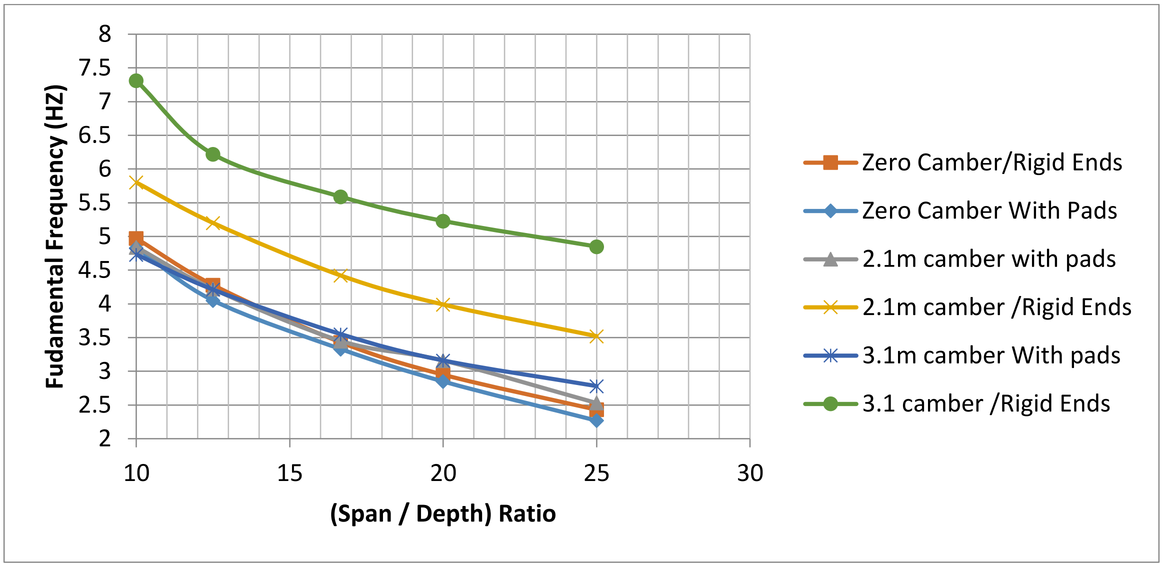



FIG. 7
FUNDAMENTAL FREQUENCIES FOR DIFFERENT BRIDGE DEPTHS

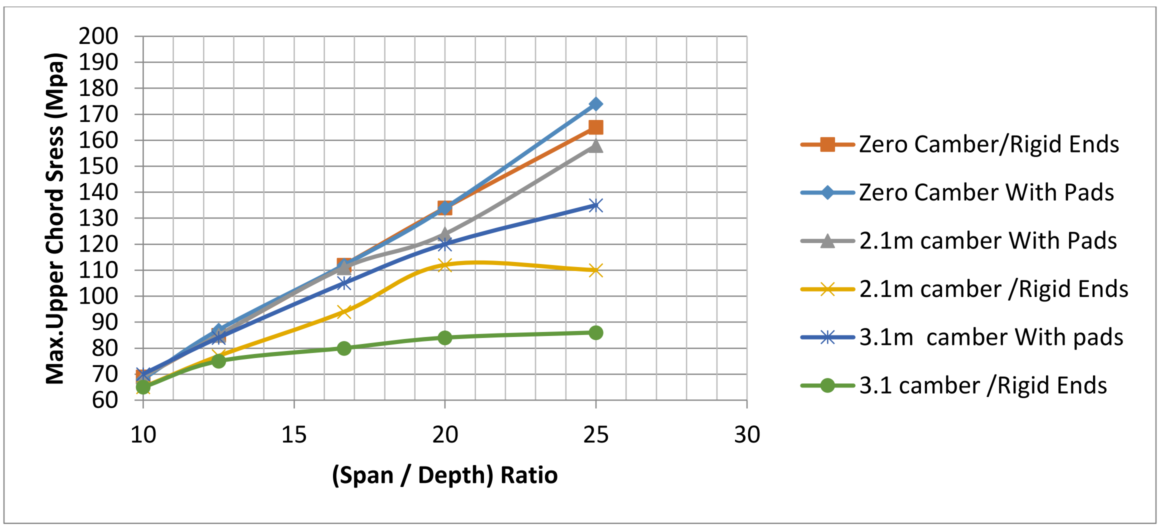



FIG. 8
MAX. UPPER CHORD STRESS (MPA) FOR DIFFERENT BRIDGE DEPTHS

TABLE 3
EFFECT OF DECK CAMBER & SUPPORT TYPE ON MAX.UPPER CHORD STRESS (MPA)

| **Bridge Type** | | **Max. Stresses (MPa) for Different (Span / Depth) Ratios** | | | | |
|---|---|---|---|---|---|---|
| | | **23.80** | **20.00** | **16.66** | **12.50** | **10.00** |
| **Zero Camber** | **With Elastomeric Pads** | **174$^{(1)}$, 177$^{(5)}$** | **134$^{(1)}$, 135$^{(5)}$** | **112$^{(1)}$,114$^{(5)}$** | **87$^{(1)}$ 89$^{(5)}$** | **68$^{(1)}$ 70$^{(5)}$** |
| | **Rigid Ends** | **165$^{(1)}$ 172$^{(5)}$** | **134$^{(1)}$ 139$^{(5)}$** | **112$^{(1)}$ 117$^{(5)}$** | **85$^{(1)}$ 90$^{(5)}$** | **69$^{(1)}$ 73$^{(5)}$** |
| **2.1m Camber** | **With Elastomeric Pads** | **158$^{(1)}$ 172$^{(5)}$** | **124$^{(1)}$ 131$^{(5)}$** | **111$^{(1)}$ 121$^{(5)}$** | **85$^{(1)}$ 92$^{(5)}$** | **69$^{(1)}$ 75$^{(4)}$** |
| | **Rigid Ends** | **110$^{(1)}$ 150$^{(5)}$** | **112$^{(1)}$ 150$^{(5)}$** | **94$^{(1)}$ 134$^{(5)}$** | **77$^{(1)}$ 111$^{(5)}$** | **65$^{(1)}$ 93$^{(5)}$** |
| **3.1m Camber** | **With Elastomeric Pads** | **135$^{(1)}$ 159$^{(5)}$** | **120$^{(1)}$ 133$^{(5)}$** | **105$^{(1)}$ 106$^{(5)}$** | **84$^{(1)}$ 99$^{(5)}$** | **70$^{(1)}$ 82$^{(5)}$** |
| | **Rigid Ends** | **86$^{(1)}$114$^{(5)}$** | **84$^{(1)}$ 111$^{(5)}$** | **80$^{(1)}$ 106$^{(5)}$** | **75$^{(1)}$ 96$^{(5)}$** | **65$^{(1)}$ 86$^{(5)}$** |

**(1) Load combination 1.** **(4) Load combination 4.** **(5) Load combination 5.**

TABLE 4
EFFECT OF DECK CAMBER & SUPPORT TYPE ON FUNDAMENTAL FREQUENCY (HZ)

| **Bridge Type** | | **Fundamental Frequency (HZ) for Different (Span / Depth) Ratios** | | | | |
|---|---|---|---|---|---|---|
| | | **23.80** | **20.00** | **16.66** | **12.50** | **10.00** |
| **Zero Camber** | **With Elastomeric Pads** | **2.27** | **2.85** | **3.33** | **4.05** | **4.83** |
| | **Rigid Ends** | **2.43** | **2.95** | **3.43** | **4.28** | **4.97** |
| **2.1m Camber** | **With Elastomeric Pads** | **2.53** | **3.04** | **3.45** | **4.22** | **4.84** |
| | **Rigid Ends** | **3.52** | **3.99** | **4.42** | **5.20** | **5.80** |
| **3.1m Camber** | **With Elastomeric Pads** | **2.78** | **3.16** | **3.55** | **4.21** | **4.73** |
| | **Rigid Ends** | **4.85** | **5.23** | **5.59** | **6.22** | **7.31** |

TABLE 5
EFFECT OF DECK CAMBER & SUPPORT TYPE ON LIVE LOAD DEFLECTION (MM)

| **Bridge Type** | | **Live Load Deflection (mm) for Different (Span / Depth) Ratios** | | | | |
|---|---|---|---|---|---|---|
| | | **23.80** | **20.00** | **16.66** | **12.50** | **10.00** |
| **Zero Camber** | **With Elastomeric Pads** | **106** | **71** | **51** | **31** | **22** |
| | **Rigid Ends** | **92** | **63** | **46** | **29** | **21** |
| **2.1m Camber** | **With Elastomeric Pads** | **90** | **64** | **46** | **29** | **21** |
| | **Rigid Ends** | **50** | **37** | **30** | **21** | **16** |
| **3.1m Camber** | **With Elastomeric Pads** | **70** | **57** | **42** | **27** | **22** |
| | **Rigid Ends** | **25** | **21** | **18** | **14** | **12** |

## 4. CONCLUSIONS

From this study the following conclusions can be obtained: -

1. The use of arched deck increases the bridge global stiffness and consequently increases its fundamental frequency. For rigid end bridges (without elastomeric pads) this effect is more pronounced as compared with arched deck bridges supported on elastomeric pads.
2. The results indicate that footbridges satisfying the service stress limitation may not necessarily satisfy the minimum value of fundamental frequency as specified in codes of practice.
3. The effects of deck camber, type of support, (span/depth) ratio and the analysis methodology may be adopted for other footbridge types. Axiomatically, there is no unique answer about the percentage effect of these analysis parameters for

all bridge types. Accordingly, for any footbridge a parametric study is necessary to find the bridge properties and geometry for which the serviceability state is deemed to be acceptable.

4. For the 50m span steel footbridge considered in the present study, the cases of flat deck resting on elastomeric pads are considered as a reference cases for comparison among other cases. The following conclusion are drawn: -
   a- For rigid ends and 2.1 m camber cases, the stress reductions are 37%, 16%, 14%, 12% and 4% and the increase in fundamental frequencies are 55%, 40%, 33%, 28% and 20% respectively for (span/ depth) ratios of 23.8, 20.0, 16.6, 12.5 and 10.0
   b- When the deck camber has been increased to 3.10 m, the stress reductions become 51%, 37%, 29%, 14% and 4% and the increases in the fundamental frequency are 114%, 84%, 68%, 54%, and 51% respectively.

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