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PIN CLEARANCE EFFECT IN TOTAL DISPLACEMENTS OF DEPLOYABLE BRIDGES

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ABSTRACT: The "Bailey Bridge" which is named by its designer, is a deployable steel truss bridge consisted of prefabricated parts. This type of bridge was manufactured and used during the World War II, initially for military use. It was such an adjustable construction either in gaps or in loading capacity that made it popular among engineers. All the parts of Bailey bridge such as panels or transoms are connected to each other with bolts, pins and clamps. The aim of this study is to determine how the pin clearance affects the total displacement of the structure. Some measures of displacements, in situ, are not in accordance with the theoretical results which take into account only the dead load and the effect of shear forces. This diversion is caused by the lack of equations of pin clearance affection.

KEYWORDS: Truss bridges; pin clearance; total displacements.

1 INTRODUCTION

The vertical displacements of steel bridges are studied, by engineers, either during the construction or the usage of bridge.

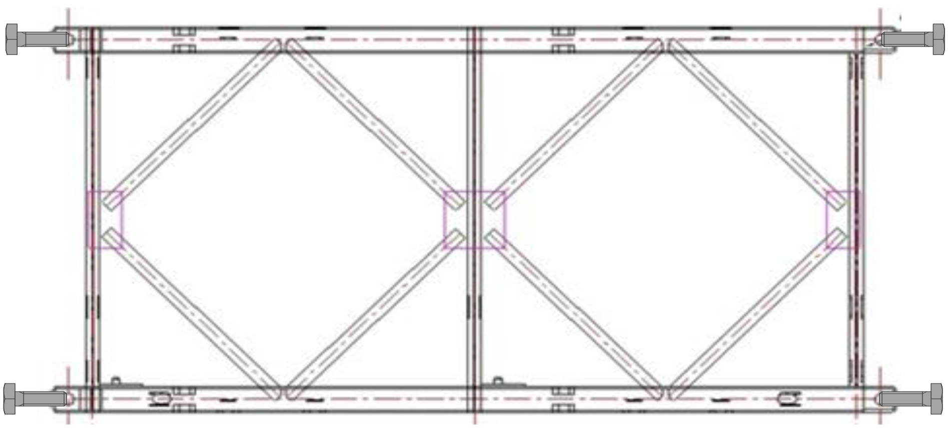

Figure 1. Bailey bridge Panel

The initial displacements due to dead load are calculated by equations which take into account uniform dead load, the elastic modulus and length as well. The Bailey bridge is constructed by two main truss beams each of them is consisted of panels, as shown in Figure 1, with 4 corner holes.

2 DESCRIPTION OF BRIDGE

2.1 General

Bailey bridges are built on site from a pre-engineered system of ready-to-assemble components. Utilizing standardized prefabricated components, Bailey bridges can be built to match a wide range of vehicular bridging applications. Because of their excellent versatility and overall value, thousands of Bailey bridges have been installed throughout the world [1]. Pinned panels consist the two main girders where the wooden deck leaning. A number of transoms are used to carry the loading to girders. There are two launching procedures for every type of Bailey bridge. The first one is the launching by cantilever and the second is by using crane to put the bridge on abutments but in this case, the bridge is pre-assembled.

2.2 Bailey bridge Parts

There are 33 main parts and tools of Bailey bridge and a number of pins and bolts, which are used. In Figure 2 are presented some of them. Also in figure 3 are presented 7 different types of Bailey bridges. Each of them consists of the same parts but there is a difference in the number of them [2].

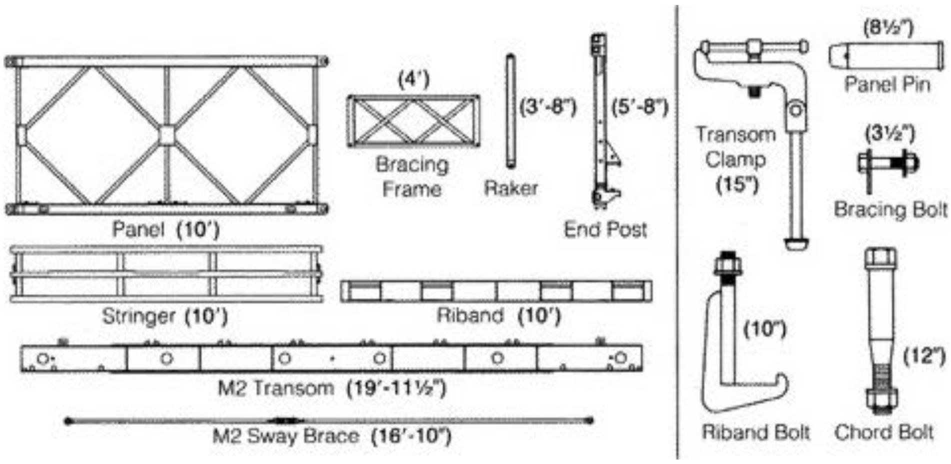

Figure 2. Main parts and bolts of Bailey bridge (source: FM 5-277)

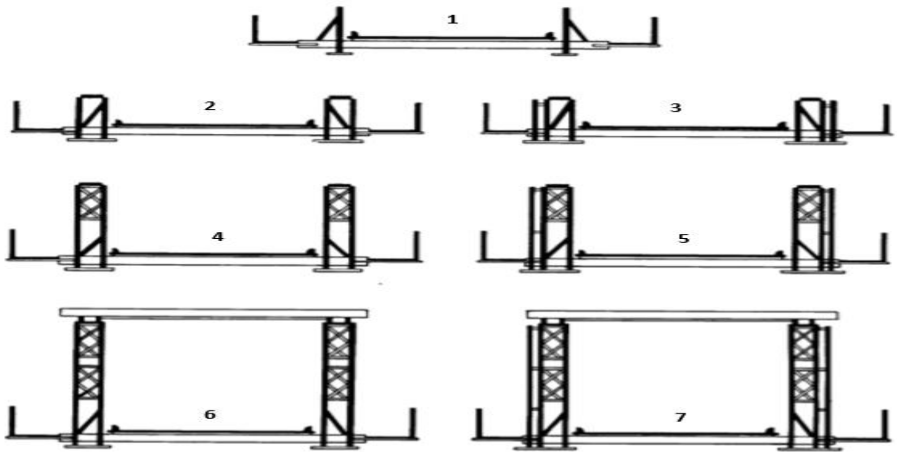

Figure 3 Types of Bailey Bridge (source: FM 5-277)

2.3 Features of Bailey bridge

According to EC-3 the moment of inertia for truss beams are calculated by the equation 1 [5].

$$I_{eff} = 2 \cdot A_f \cdot \left(\frac{h_0}{2}\right)^2 \tag{1}$$

where: A_f Area of chord cross section=3083,2 mm^2 (2)

h_0 centroid of bottom chord to centroid of top chord=1447 mm (3)

According to equations (1),(2),(3) the result for the effective moment of inertia is:

$$I_{eff} = 3{,}23 \cdot 10^9 \, mm^4 \tag{4}$$

The main parts of bridge, like panels and transoms, are made by steel BS 968 instead of the other members which are made by BS 15.

Table 1. BS 968 mechanical properties

Property	Material	Value
Elastic Modulus	Steel BS 968	206,8 GPa
f_y	Steel BS 968	344 MPa
f_u	Steel BS 968	540 MPa

3 THE DISPLACEMENTS IN SIMPLY SUPPORTED TRUSS BRIDGES

3.1 General

The displacements in a simply supported truss bridge are calculated by equations:

$$W_g = \frac{5pL^4}{384EI} mm \tag{5}$$

$$W_V = \frac{pL^2}{8S_V} \tag{6}$$

where: W_g displacements due to dead load (7)

W_v displacements due to shear forces (8)

In case of truss bridges, it is necessary to take into account the value of the displacements as the cross section, which receives the shear forces, is limited. The shear stiffness S_V of this form of girders is calculated with the following procedure:

3.1.1 Applying in a FEM model of a girder a single transverse force.

3.1.2 Calculating the axial forces of members by analysis.

3.1.3 Determining the lateral displacement of a bay with following equation

$$\delta_s = \sum \int \frac{N^2}{EA} d_x \tag{9}$$

Where N Axial forces of members

A Cross section Area

The total shear displacement of bay with height α is equal to:

$$\phi_V = \frac{\delta_s}{a} \tag{10}$$

Then S_v is calculated by the equation below:

$$S_v = \frac{V}{\phi_v} = \frac{1}{\phi_v} \tag{11}$$

A percentage of total displacement is the effect of pin clearance. The proportion of this type of displacement until now was calculated according to the equation:

$$Wpin\_clearance = \frac{0{,}5 \cdot L \cdot d_o}{h \cdot \cos a} \tag{12}$$

where: α the angle between vertical and diagonal members.

It can be observed that the results between the theoretical approach and field measurements have a variance that could be assigned to pin clearance affection. As the equations (5),(6) have been proved in the past, the only obvious reason for the variance of displacement is the pin clearance effect.

3.2 The displacements due to pin clearance effect

This study is focused to type Single-Single of Bailey bridge where the girders consist of panels pinned at corners. In the other types of Bailey bridges with storeys more than one, like Double-Double or Triple-Double, the pin clearance effect is more complicated as long as there are different types of parts used. These parts as bolt cords or bracing frames affect to displacements.
Each girder assembled with panels with the following features:

where: n number of panels

- L distance between the centers of holes along the panel
- h distance between the center of holes at height of the panel
- d hole diameter
- d_1 pin diameter
- d_2 pin clearance
- d_o $(d_1\text{-}d_2)$: pin clearance

First of all it should be mentioned that there are two different conditions of a Bailey structure as shown in Figure 4.

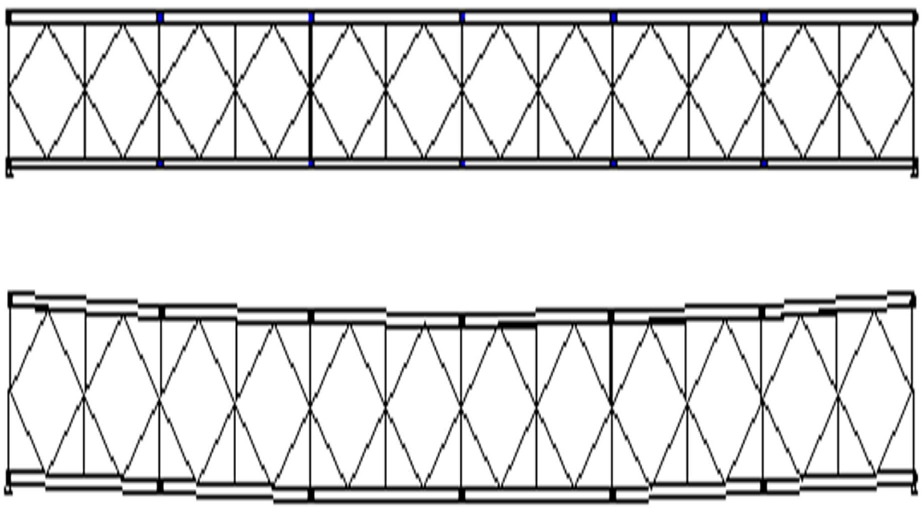

Figure 4 Deformed and non-deformed condition of Bailey bridge

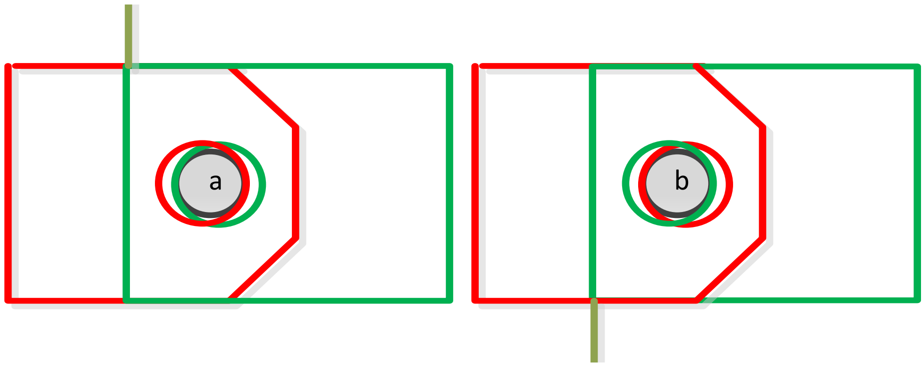

Figure 5 Pin position at a) bottom joint b) top joint

Also in figure 5 is showed the pin position in relevance to the holes of two panels. Therefore due to pin clearance and the bending of each girder the total length of bottom chord is increasing by the amount of n*2d_o when the top chord length is decreasing by the amount of n*2d_o. In order to create equations for displacement's calculation in a close form due to pin clearance effect the following procedure can be applied:

a. Assume the structure in the undeformed condition and the pin position in the initial form, as shown in Figure 6a.

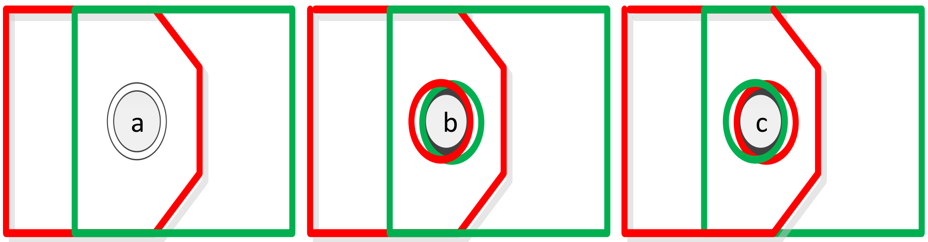

Figure 6 Bottom Joint at different positions of pin

b. At the next step, the second panel rotates in comparison with the first one remains to its initial position.

At this phase, the joint condition has the same view as Figure 6b at the bottom joint and the Figure 6c at the top joint.

This progressive procedure, take place each time, with a distinctive angle like Figure 7, 8 which is calculated by the equation

$$\phi = Arc\tan(\frac{2 \cdot d_o}{h}) \tag{13}$$

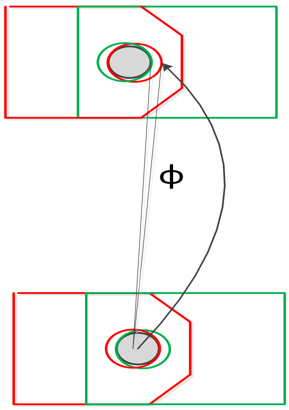

Figure 7 Rotation angle

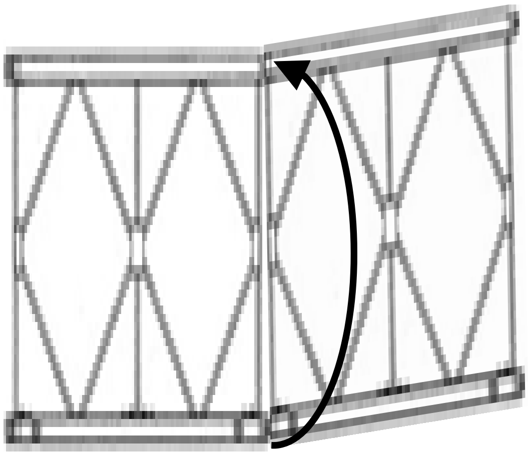

Figure 8 Rotated panel

This angle is the same for every step as it is the relative angle for panels side by side. This procedure is followed for all the panels. The angle between panels is calculated by the equation 10 for all panels, except the first two, the angle is equal to $(n_f - 1) \cdot \phi$ where f: 2, 3..,n. In Figure 9 with green color is the panel, which is rotated each time.

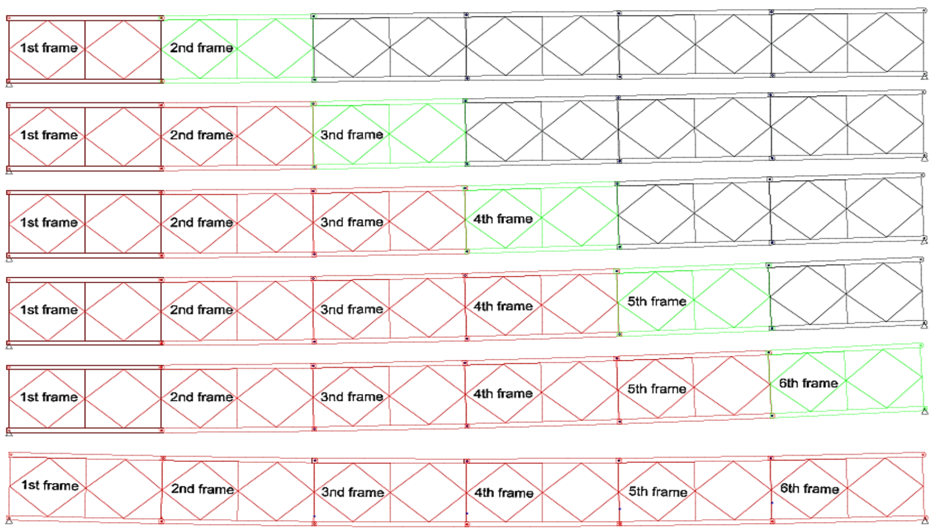

Figure 9 Frame rotation process

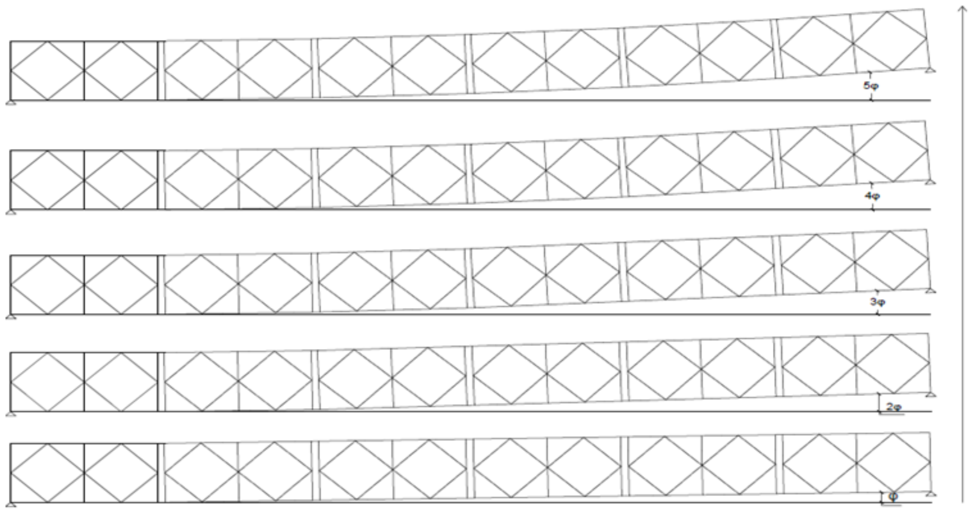

Figure 10 A Simplified schematic diagram for a six-panel bridge

In Figure 10 it is obvious that the last panel rotate in comparison with the first one with the angle (n-1)φ.

where: n the number of the panels

φ the angle from equation 10.

c. From the geometry of fig. 10 founding that the angle for the first panel is:

$$\frac{n-1}{2} \cdot \phi \tag{14}$$

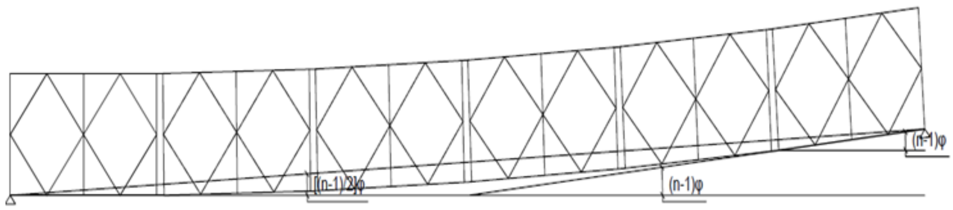

Figure 11 Geometry of transformed structure (Bottom panel's chords with red color)

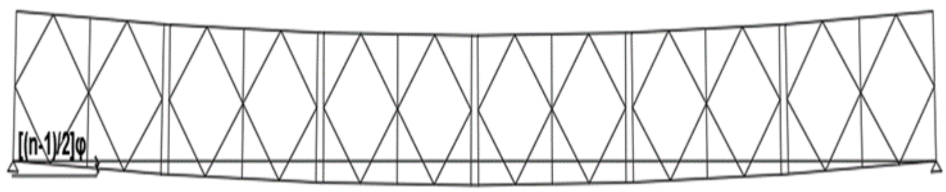

Figure 12 The simplified structure in final position

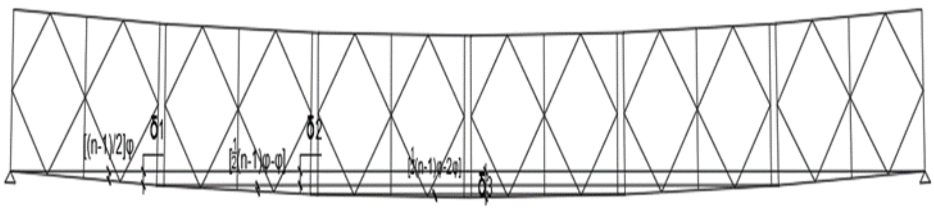

Figure 13 Schematic of relation between displacements δ and angle φ

From the figures above and the equation (11) , it is obvious that the angle and displacement for the first panel the angle is:

$$\frac{n-1}{2}\cdot\phi \tag{15}$$

$$\delta_1 = \tan(\varphi_1)\cdot \mathrm{L} = \tan(\frac{\mathrm{n}-1}{2})\cdot L - \frac{d_0}{4}\cdot\tan(\phi) \tag{16}$$

Where: $\frac{d_o}{4}\cdot tan(\phi)$ is the correction factor due to pin position.

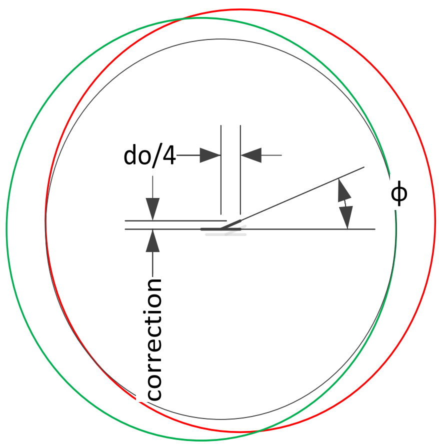

Figure 14 Correction factor

The angle and displacement for the second panel the angle is:

$$\phi_2 = \frac{n-1}{2}\cdot\phi - \phi = \frac{n-3}{2}\cdot\phi \tag{17}$$

$$\delta_2 = tan(\varphi_2)\cdot L - \frac{d_0}{4}\cdot tan(\phi) \tag{18}$$

The angle and displacement for the third panel the angle is:

$$\phi_3 = \frac{n-1}{2} \cdot \phi - 2\phi = \frac{n-5}{2} \cdot \phi \tag{19}$$

$$\delta_3 = tan\,(\varphi_3\,) \cdot L - \frac{d_0}{4} \cdot tan(\,\phi\,) \tag{20}$$

The angle and displacement for the $\frac{n}{2}$ th panel is needed to be separated in two different cases.

a. The first one for the bridges with even number of panels in each girder

$$\phi' = \frac{\text{n -1}}{2} \cdot \phi - (\frac{n}{2} - 1) = \frac{1}{2} \cdot \phi \tag{21}$$

$$\delta_{\frac{n}{2}} = \tan(\frac{1}{2} \cdot \phi) \cdot L \tag{22}$$

In this case there is no correction as the center of pin is at the lower position.

b. The second one, with even number of panels in each girder

$$\phi' = \frac{\text{n -1}}{2} \cdot \phi - (\frac{n}{2} - \frac{3}{2}) \cdot \phi = \phi \tag{23}$$

$$\delta_{\frac{n}{2}} = \tan(\phi) \cdot L_2 - \frac{d_o}{4} \cdot \tan(\phi) \tag{24}$$

$$\delta_{tot} = \left[\sum_{k=1}^{k=\frac{n}{2}} \tan(\frac{n-(2k-1)}{2}\phi)) \right] \cdot L - (\frac{n}{2} - 1) \cdot \frac{d_o}{4} \cdot \tan(\phi), \text{n : even} \tag{25}$$

$$\delta_{tot} = \left[\sum_{k=1}^{k=\frac{n}{2}} \tan(\frac{n-(2k-1)}{2}\phi)) \right] \cdot L - (\frac{n}{2} - \frac{1}{2}) \cdot \frac{d_o}{4} \cdot \tan(\phi), \text{n : odd} \tag{26}$$

with the replacements of the previous equations

$$\delta_{tot,even} = \left[\sum_{k=1}^{k=\frac{n}{2}} \tan(\frac{n-(2k-1)}{2} \cdot Arc\tan(\frac{2d_o}{h}))) \right] \cdot L - (\frac{n-2}{4}) \cdot \frac{d_o^2}{h} \tag{27}$$

$$\delta_{tot,odd} = \left[\sum_{k=1}^{k=\frac{n}{2}} \tan(\frac{n-(2k-1)}{2} \cdot Arc\tan(\frac{2d_o}{h}))\right] \cdot L - (\frac{n-1}{4}) \cdot \frac{d_o^2}{h} \qquad (28)$$

3.3 Numerical Example of a six panel Single-Single Bailey bridge

The total deflection of six panel single-single Bailey bridge is calculated by the equation:

$$\delta_{comp,total} = W_g + W_V + \delta_{tot} \qquad (29)$$

$$\delta_{comp,total} = \frac{5pL^4}{384EI} + \frac{pL^2}{8S_V} + \left[\sum_{k=1}^{k=\frac{n}{2}} tan(\frac{n-(2k-1)}{2} \cdot Arctan(\frac{2d_o}{h}))\right] \cdot L - (\frac{n-1}{4}) \cdot \frac{d_o^2}{h} \qquad (30)$$

The features for this type of bridge are:

h : 1550 mm
L : 3048 mm
E : 206,8 Gpa
I : $6{,}46 \cdot 10^9$ mm^4 (for two girders)
p : $9{,}06 \cdot 10^{-3} \frac{kN}{mm}$:($\frac{27{,}6kN*6\ frames}{18{,}288m}$)
S_V : 59.765 kN · 2 girders=119.530 kN
do : 0,55mm is the average pin clearance of ten different measures at panels.

$$\delta_{comp,total} = \frac{5 \cdot 0{,}00906 \cdot 18288^4}{384 \cdot 206{,}8 \cdot 6{,}46 \cdot 10^9} +$$

$$\frac{0{,}00906 \cdot 18288^2}{8 \cdot 119530} +$$

$$\begin{bmatrix} (tan(\frac{6-(2-1)}{2} \cdot Arctan(\frac{2 \cdot 0{,}55}{1550}))) \\ +(tan(\frac{6-(4-1)}{2} \cdot Arctan(\frac{2 \cdot 0{,}55}{1550}))) \\ +(tan(\frac{6-(6-1)}{2} \cdot Arctan(\frac{2 \cdot 0{,}55}{1550}))) \end{bmatrix} \cdot 3048 \qquad (31)$$

$$-\frac{(6-2) \cdot 0{,}55^2}{2 \cdot 1550} = 9{,}88 + 3{,}17 + 5{,}41 + 3{,}24 + 1{,}08 - 0{,}00019 = 22{,}8mm$$

The comparison between these results, with the measurement in situ (27 mm), for the same structure indicates a difference equal to 4,2 mm (15,55%). This difference is easy to be explained as the pin clearance assumed to be equal to 0,55mm for every joint, independently of the extension due to loading. In addition this result is more close to the reality while the calculation of the displacement with equation (5) give a deflection equal to 3,24mm for angle a=0º or 4,29 mm for angle a=45º. This assumption may lead to an estimation error from 52, 3% to 66, 7% for deflection due to pin clearance affection.

3.4 Parametrical approach of displacements

At the Figure 15 are shown the deflections due to dead loading in a single-single Bailey bridge. This figure depicts the calculations from 2 to 10 panel bridge in each girder.

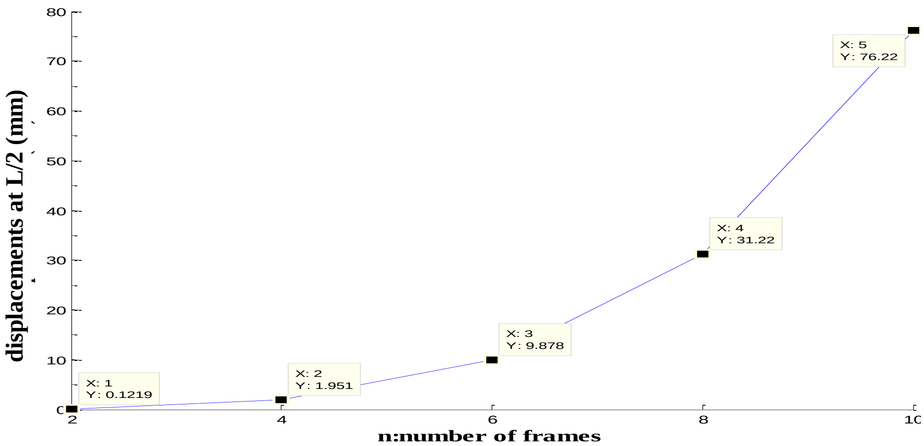

Figure 15 Deflections due to dead loading for even number of panels

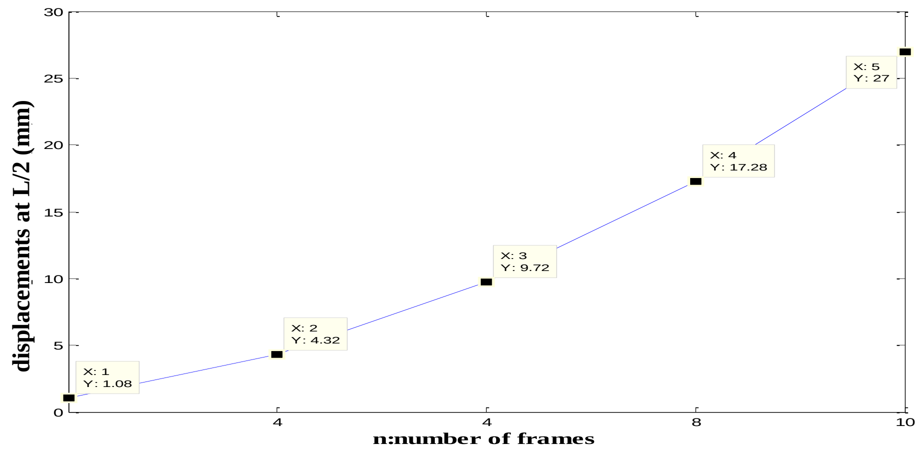

Figure 16 Deflections due to pin clearance affection for even number of panels

*Table 2. C*omparison table of displacements

number of frames	w_g (mm)	w_v (mm)	δ_{tot} (mm)	$\delta_{comp\ total}$ (mm)	$\frac{w_g}{w_v}$	$\frac{w_g}{\delta_{tot}}$
2	0,122	0,352	1,08	1,554	0,35	0,11
4	1,951	1,408	4,32	7,679	1,39	0,45
6	9,878	3,169	9,72	22,8	3,12	1,02
8	31,22	5,633	17,28	54,13	5,54	1,81
10	76,22	8,802	27	112,02	8,66	2,82

In figure 17 it is obvious that the single-single type of Bailey bridge presents a larger amount of displacements than the other two types of single form in width, like the Double-Single and the Triple-Single form. This means that in girders with greater stiffness the displacements, due to pin clearance, are bigger in comparison with the other components of displacement.

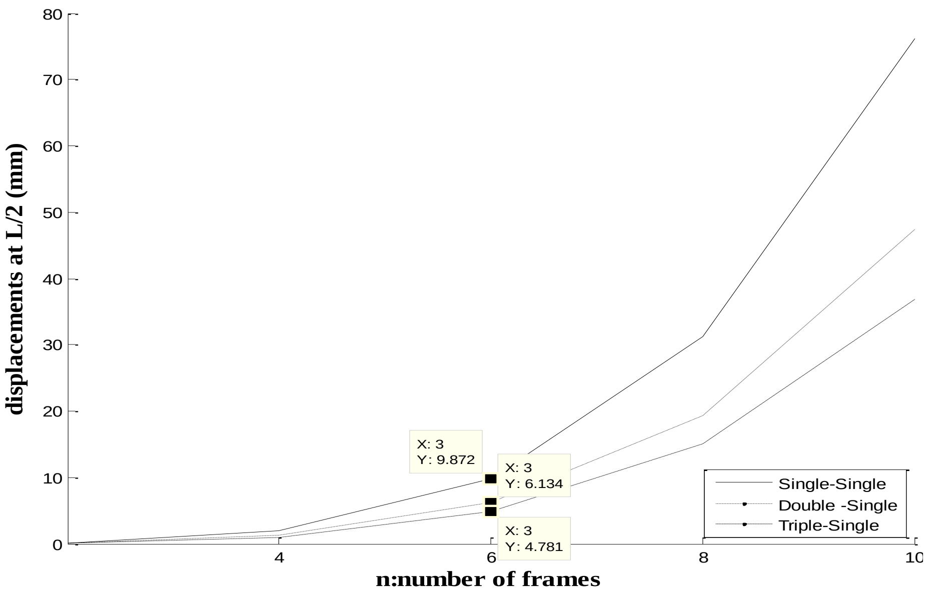

Figure 17 Deflections due to dead loading for three different types of Bailey bridge

Assuming the ratio $0{,}01 \leq \frac{h}{L} \leq 1$ where L and δo are constant, then the diagrams are shown in Figure 18.

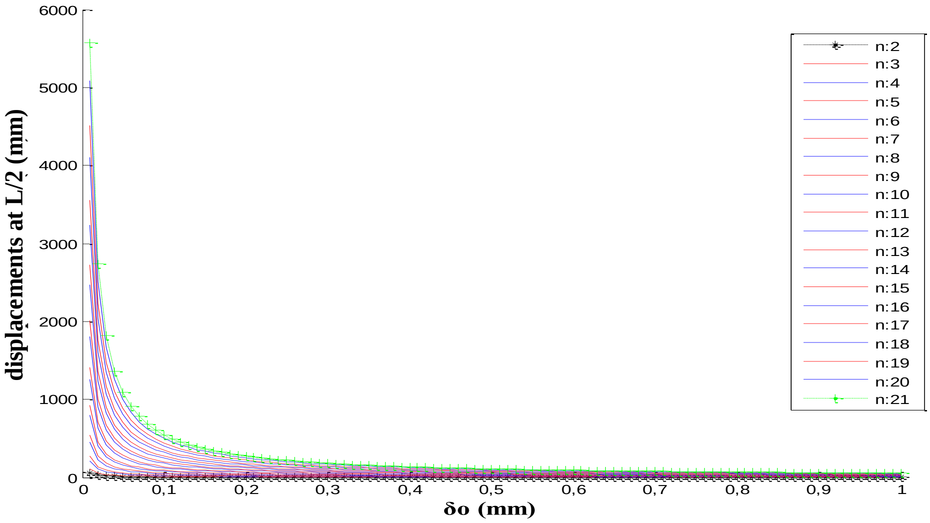

Figure 18 The deflection of a Single-Single Bailey bridge with constant δ_o=0,55 mm *and ratio* $\mathbf{0,01 \leq \frac{h}{L} \leq 1}$

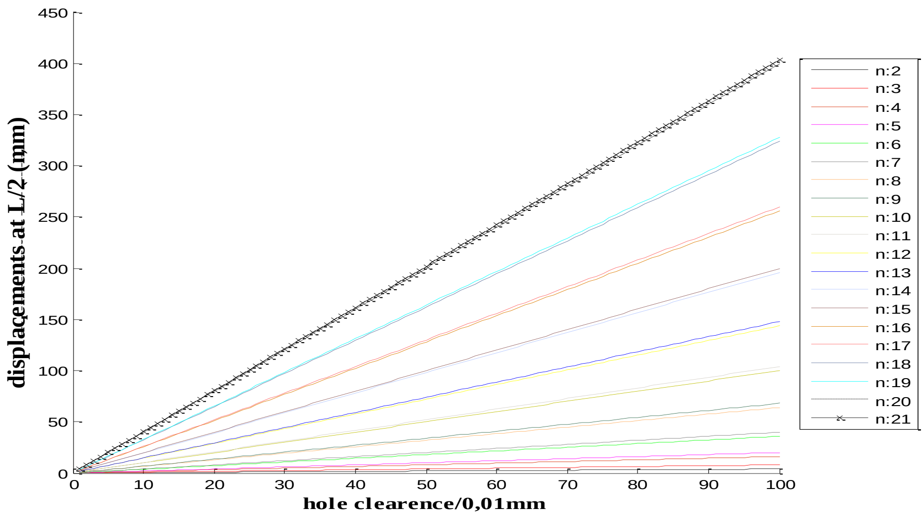

Figure 19 Deflection of a Single-Single Bailey bridge with *ratio* $\mathbf{0,01 \leq \delta o \leq 1}$

From the figure 19 are produced the equation of table

Table 3. Parameterization of the equations

number of panels (NoP)	Equation δ_{tot}
2	$\delta_{tot} = 1{,}95\delta o + 0{,}0001$
3	$\delta_{tot} = 3{,}95\delta o + 0{,}0001$
4	$\delta_{tot} = 7{,}87\delta o + 0{,}0003$
5	$\delta_{tot} = 9{,}85\delta o + 0{,}0003$
6	$\delta_{tot} = 17{,}7\delta o + 0{,}0005$
7	$\delta_{tot} = 19{,}7\delta o + 0{,}0004$
8	$\delta_{tot} = 31{,}45\delta o + 0{,}0006$
9	$\delta_{tot} = 33{,}45\delta o + 0{,}0005$
10	$\delta_{tot} = 49{,}15\delta o + 0{,}0005$
11	$\delta_{tot} = 51{,}15\delta o + 0{,}0004$
12	$\delta_{tot} = 70{,}8\delta o + 0{,}0001$
13	$\delta_{tot} = 72{,}75\delta o - 0{,}00004$
14	$\delta_{tot} = 96{,}35\delta o - 0{,}0006$
15	$\delta_{tot} = 98{,}35\delta o - 0{,}0008$
16	$\delta_{tot} = 125{,}85\delta o - 0{,}0018$
17	$\delta_{tot} = 127{,}85\delta o - 0{,}0021$
18	$\delta_{tot} = 159{,}3\delta o - 0{,}0037$
19	$\delta_{tot} = 161{,}25\delta o - 0{,}0041$
20	$\delta_{tot} = 196{,}65\delta o - 0{,}0065$
21	$\delta_{tot} = 198{,}65\delta o - 0{,}007$

4 CONCLUSIONS

In this paper, two equations are proposed for the calculation of the deflection in deployable steel bridges like the type of Bailey bridge. With these two equations, it is becoming possible to predict the deflection of these types of bridges with more accuracy in comparison with the other case where the deflection is calculated as a result of rotating girder.

1) From the parametric approach, it is found that by increasing the stiffness the affection to the deflection is smaller than the case with lower stiffness.
2) The deflection due to pin clearance is bigger for specific number of bays compared to dead load effect.
3) By the equations which have been exported it is obvious that any variance to pin clearance can cause proportional increasing to deflection.
4) All these equations are result assuming that the pin clearance is constant. Generally the pin clearance appears to vary due to loading which causes even greater increase in displacement.

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