Analysis of Different Bascule Bridge Architectures

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Abstract: - Bascule bridges are widely used nowadays to overcome the obstruction of ships passage as crossing waterways and in some roadways to overcome transport vehicle height limitation. A Bascule bridge is a movable bridge with a counterweight that continuously balances a span, or "leaf", throughout its upward swing to provide clearance for boat or ship traffic. It may be single or double leafed. Balance Beam Bascule Bridge is one of the famous bascule bridge architecture in which bridge span counter balance weight is attached to a balance beam in the movable bridge operating mechanism. Although hydraulic cylinders is a particularly common solution to power majority of modern bascule bridges, it is very important to understand the kinematics and motion of the bridge leave for optimum operation of the bridge with prober counter balance selection. In this study a review of two operating hydraulic actuators arrangements; push arrangement and pull arrangement is carried out based on both design aspects and safety consideration. 3D model of the study mechanisms are constructed and a kinematics of bridge leaf (span) opening mechanisms are developed for early stage design configuration of bridge mechanism. kinematic analyses of bridge mechanism operation in both push and pull arrangements based on rigid body consideration is performed and Numerical analysis using finite element method is carried out in which stress distribution over tie rods is obtained. Some failure scenarios are introduced. Results show that tension forces acting on tie rods in pull arrangement is lower than that in push arrangement, work done by hydraulic cylinders (Actuators) in both arrangement is nearly identical and pull arrangement is much better than push arrangement from safety point of view.

Key-Words: - Bascule bridge, beam balanced bridge, movable bridge, Bridge mechanism, bridge balance, failure assessment.

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1 Introduction

Movable bridges or partially movable bridges are used widely where the bridge contradict waterways and obstruct ships passage. Three basic types of movable bridges are generally designed and built today –bascule bridges, swing bridges and vertical lift bridges. Bascule bridges mainly Rotates around the horizontal axis while swing bridges Rotates around the vertical axis. Regardless of the type of movable bridge selected, span weight and balance are critical issues. In order to minimize the size and power requirements needed to operate a movable bridge, movable spans for vertical lift and bascule bridges are typically counterweighted to reduce a balanced condition. This allows drive machinery to be sized to only overcome small intentional imbalances, rather than the full weight of the movable span, in addition to frictional resistances, and wind and ice loads. Counterweights are installed in order to minimize the size of the mechanical power transmission system components needed to operate the bridge, and to provide a relative measure of safety in the event of failure in the mechanical system. The position of this counterweight depends on the type of Bascule bridge. There are four main types of bascule bridge [1] are depicted in Fig.1.

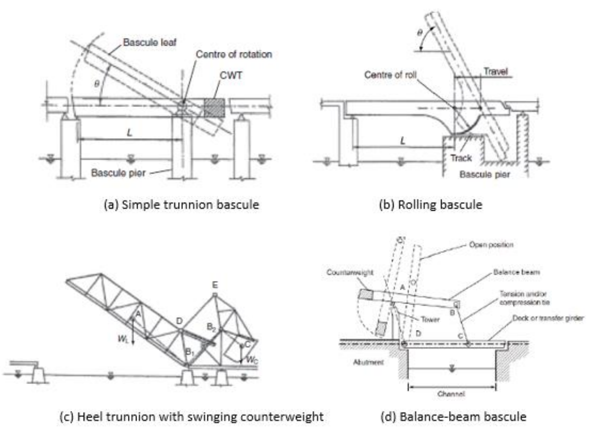


Fig. 1: Types of bascule bridges [1].

A new type for mobile stayed bridges: the piston-stayed bridge is introduced [2]. The engineering design innovation of the piston-stayed bridge lies in the use of one single element, i.e. the piston stay, for actuation as well as support of the mobile bridge section as shown in Fig.2. At the design stage it is proposed to apply simulation modeling in order to determine optimum law of drive control.

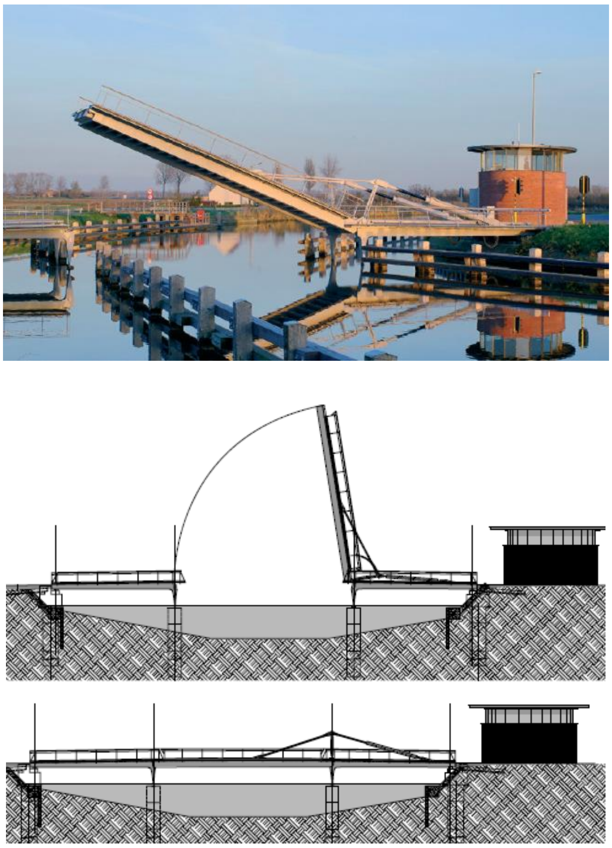


Fig. 2: Piston-stayed bridge

Dynamics of power processes of hydraulic lifting mechanisms upon motion of a single-wing bascule bridge based on different algorithms for automatic control is discussed [3] showing that the coefficients of dynamicity significantly affected by bridge mechanism dynamics. Based on appropriate counter balance mechanism and proper material, a comparative study is conducted between stainless steel and structural steel used for construction of Bascule Bridge considering stress and strain acting on the bridge along with the total deformation analysis [4]. Bridge structure health monitoring along with operational parameters control is introduced [5] in order to maintain proper operation of the bridge and as extend including variable operational parameter such as wind speed and direction during bridge span rotation for proper control of operation mechanism. Movable components such as hydraulic cylinders, bridge span and span lock for double leave Bascule bridges are shown to be of the most critical components [6].

2 Study Cases

In this study two different bascule bridge architectures are considered based on lifting mechanism hydraulic cylinders arrangements which are: (1) Cylinders in push arrangement; in which hydraulic cylinders are attached to the balance-beam such and push the beam to rotate it around its pivot and hence the balance-beam pull bridge leaf via tie rods connecting the balance-beam and the bridge leaf causing bridge span opening. This case is such in Azmy Bridge, Port Said, Egypt [7] shown in Fig.3.

Fig. 3: Azmy Bridge, Port Said, Egypt

(2) Cylinders in pull arrangement; in which hydraulic cylinders are attached to bridge leaf and pull the leaf around its trunnion for bridge span opening. This case is such in Wolgast Bascule Bridge in Germany shown in Fig.4.


Fig. 4: Bascule bridge of Wolgast, Germany

Although hydraulic cylinders is a particularly common solution and the majority of modern bascule bridges and movable bridges are powered by it [8], understanding kinematics and motion of the bridge leave and the change in cylinder loadings is important for prober design of bridge lift mechanism.

3 Modeling and Analysis

In hydraulic operated balance-beam bascule bridges; lift mechanism arrangement is a key factor in optimum operation of the bridge (leaf rotates during bridge span opening and closing) and in the other hand lift mechanism should consider the change of the moment required to lift the bridge and withstand the fluctuation of wind pressure during operation. At this point modeling and simulation of designed mechanism operation at design stage is one of the important steps in design validation before production and construction stages carried on. This step is not only important for operating mechanism design but also in proper design of hydraulic system operation control to avoid overloads, dynamic effects and pressure fluctuation. Mechanism kinematics based modeling and simulation in the design stage can provide informations about motion description including forces acting on lifting mechanism during bridge span rotation, proper operation velocity for power considerations, dynamics of moving components and corresponding stress acting on it during operation.

3.1 Bridge Mechanism Kinematics

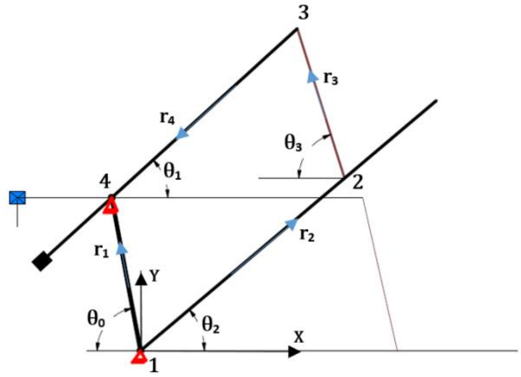


Fig. 5: Kinematics diagram of the bascule mechanism

As long as this paper consider a comparative analysis of two valid bascule bridges in a qualitative manner and not a quantitative one; some assumptions are introduced such as dealing with all components as a rigid body and ignore effect of elastic deformations. Also smooth operation eliminating inertias and dynamics effect is considered. Based on the previous assumptions; bridge mechanism can be described in 2D (planar) manner. The DOF of this mechanism can be obtained using Gruebler's formula [9] as follow;

$$F = d(n - g - 1) + \sum_{i=1}^{g} f_i \quad (1)$$

Where:

d.. number of DOF in planar = 3

n.. number of links including the frame = 4

g.. number of joints = 4

f_i.. DOF of joint i

$F = 3(4 - 4 - 1) + 4 = 1$

As obtained by equation (1); the number of degrees of freedom DOF of this mechanism is one. Loop-Closure equations can be applied Using trigonometric relations for the closed-loop r_2 r_3 r_4 r_1; forward kinematic relation of balance-beam lift angle "θ_1" due to active link (r_4) bridge leaf rotational (opening) angle "θ_2" is obtained as follow:

$$r_2 \cos\theta_2 + r_1 \cos\theta_0 = r_3 \cos\theta_3 + r_4 \cos\theta_1 \quad (2)$$
$$r_1 \sin\theta_0 + r_4 \sin\theta_1 = r_2 \sin\theta_2 + r_3 \sin\theta_3 \quad (3)$$
$$r_3 \cos\theta_3 = r_1 \cos\theta_0 + r_2 \cos\theta_2 - r_4 \cos\theta_1$$
$$r_3 \sin\theta_3 = r_1 \sin\theta_0 - r_2 \sin\theta_2 + r_4 \sin\theta_1$$
$$r_3^2 \cos^2\theta_3 = r_1^2 \cos^2\theta_0 + r_2^2 \cos^2\theta_2 + r_4^2 \cos^2\theta_1 + 2r_1 r_2 \cos\theta_0 \cos\theta_2 - 2r_1 r_4 \cos\theta_0 \cos\theta_1 - 2r_2 r_4 \cos\theta_2 \cos\theta_1 \quad (4)$$

$$r_3^2\sin^2\theta_3 = r_1^2\sin^2\theta_0 + r_2^2\sin^2\theta_2 + r_4^2\sin^2\theta_1 - 2r_1r_2\sin\theta_0\sin\theta_2 + 2r_1r_4\sin\theta_0\sin\theta_1 - 2r_2r_4\sin\theta_2\sin\theta_1 \quad (5)$$

$$r_3^2 = r_1^2 + r_2^2 + r_4^2 + 2r_1r_2\cos\theta_0\cos\theta_2 - 2r_1r_4\cos\theta_0\cos\theta_1 - 2r_2r_4\cos\theta_2\cos\theta_1 - 2r_1r_2\sin\theta_0\sin\theta_2 + 2r_1r_4\sin\theta_0\sin\theta_1 - 2r_2r_4\sin\theta_2\sin\theta_1 \quad (6)$$

$$2r_1r_4\cos\theta_0\cos\theta_1 - 2r_1r_4\sin\theta_0\sin\theta_1 + 2r_2r_4\cos\theta_2\cos\theta_1 + 2r_2r_4\sin\theta_2\sin\theta_1 - 2r_1r_2\cos\theta_0\cos\theta_2 + 2r_1r_2\sin\theta_0\sin\theta_2 = r_1^2 + r_2^2 + r_4^2 - r_3^2$$

$$2r_2r_4\sin\theta_2\sin\theta_1 + 2r_1r_2\sin\theta_0\sin\theta_2 + 2r_2r_4\cos\theta_2\cos\theta_1 - 2r_1r_2\cos\theta_0\cos\theta_2 = r_1^2 + r_2^2 + r_4^2 - r_3^2 - 2r_1r_4\cos\theta_0\cos\theta_1 + 2r_1r_4\sin\theta_0\sin\theta_1 \quad (7)$$

Set equation (7) in the form

$$\mathrm{A}\sin\theta_2 + B\cos\theta_2 = C \quad (8)$$

Where;

$$A = 2r_2r_4\sin\theta_1 + 2r_1r_2\sin\theta_0$$
$$B = 2r_2r_4\cos\theta_1 - 2r_1r_2\cos\theta_0$$
$$C = r_1^2 + r_2^2 + r_4^2 - r_3^2 + 2r_1r_4\sin\theta_0\sin\theta_1 - 2r_1r_4\cos\theta_0\cos\theta_1$$

$$\frac{A}{\sqrt{A^2+B^2}}\sin\theta_2 + \frac{B}{\sqrt{A^2+B^2}}\cos\theta_2 = \frac{C}{\sqrt{A^2+B^2}}$$

$$cos \propto cos\,\theta_2 + sin \propto sin\,\theta_2 = \frac{C}{\sqrt{A^2+B^2}}$$

$$cos(\propto -\theta_2) = \frac{C}{\sqrt{A^2+B^2}}$$

$$\propto = tan^{-1}\left(\frac{A}{B}\right)$$

$$\theta_2 = \alpha - cos^{-1}\left(\frac{C}{\sqrt{A^2+B^2}}\right) =$$

$$\theta_2 = tan^{-1}\left(\frac{A}{B}\right) - cos^{-1}\left(\frac{C}{\sqrt{A^2+B^2}}\right) \quad (9)$$

Equation (9) describes bridge leaf opening angle "θ_2" as a function of Balance-beam lift angle "θ_1" and illustrated in Fig.6 which shows relatively linear relation between balance beam rotation and bridge leaf opening.

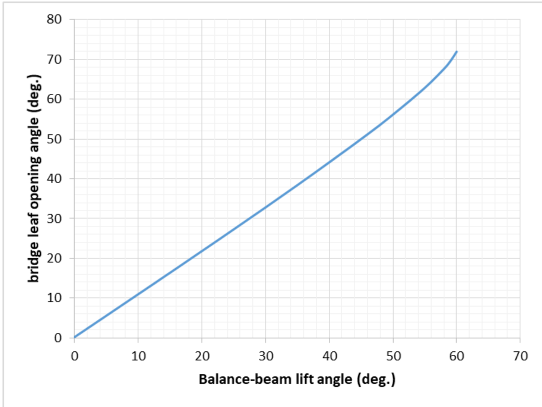
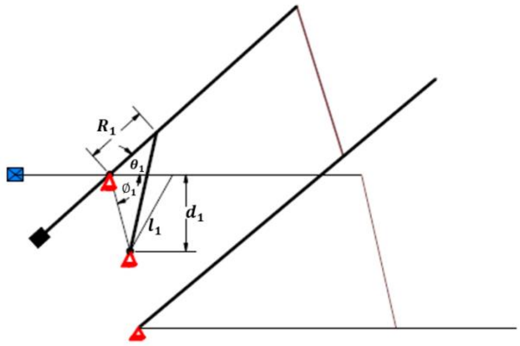
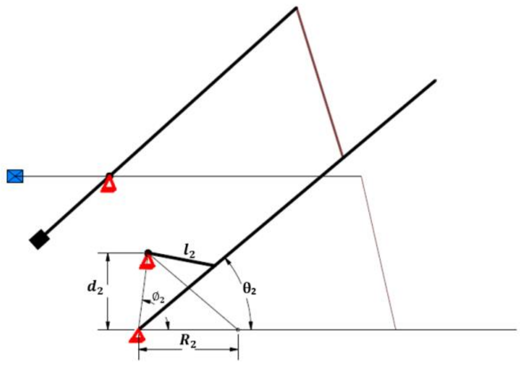


Fig. 6: Bridge leaf opening angle "θ_2" as a function of Balance-beam lift angle "θ_1"



(a) Cylinders in push arrangement



(b) Cylinders in pull arrangement

Fig. 7: Kinematics diagram of operating hydraulic cylinder

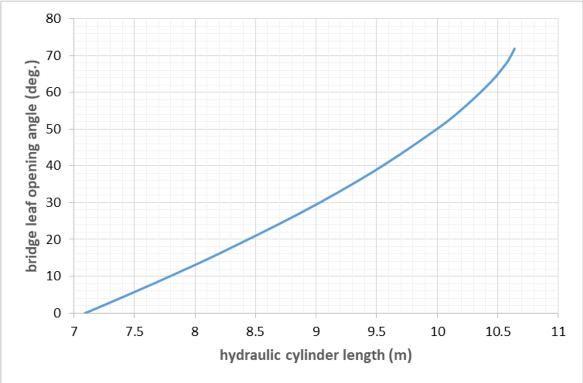
The relation between Balance-beam lift angle "θ_1" and operating hydraulic cylinder length "l_1"illustrated in Fig.7 (a) can be obtained using trigonometric relations as follow:

$$l_1^2 = \left(\frac{d_1}{sin\emptyset_1}\right)^2 + {R_1}^2 - 2R_1\left(\frac{d_1}{sin\emptyset_1}\right)cos(\emptyset_1 + \theta_1)$$

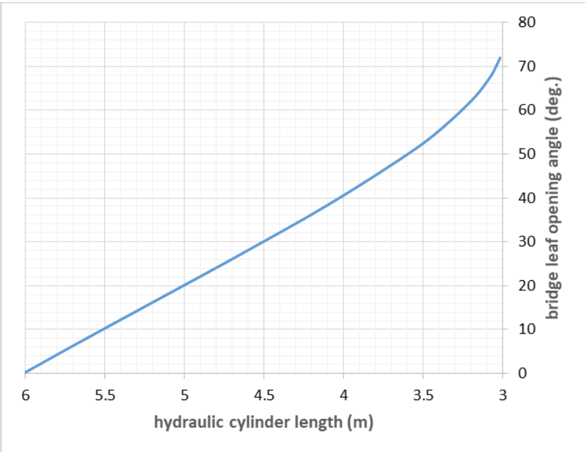
$$l_1 = \sqrt{\left(\frac{d_1}{sin\emptyset_1}\right)^2 + {R_1}^2 - 2R_1\left(\frac{d_1}{sin\emptyset_1}\right)cos(\emptyset_1 + \theta_1)} \quad (10)$$

Where:" l_1 "cylinder length at any time during operation," $\emptyset_1$ "angle of cylinder installation, "d_1" cylinder hub support vertical position and "R_1"

distance between balanced-beam pivot and cylinder rod support point.



(a) Cylinders in push arrangement



(b) Cylinders in pull arrangement

Fig. 8: Bascule mechanism operation relations

In the same way; the relation between Balance-beam lift angle "θ_2" and operating hydraulic cylinder length "l_2"in pull arrangement illustrated in Fig.7 (b) can be obtained as follow:

$$l_2 = \sqrt{\left(\frac{d_2}{sin\emptyset_2}\right)^2 + {R_2}^2 - 2R_2\left(\frac{d_2}{sin\emptyset_2}\right)cos(\emptyset_2 - \theta_2)} \quad (11)$$

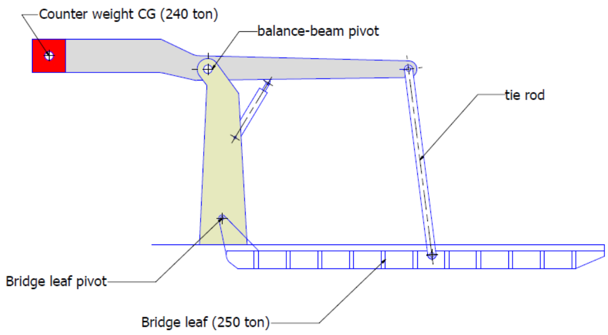
Where:" l_2 "cylinder length at any time during operation," $\emptyset_2$ "angle of cylinder installation, "d_2" cylinder hub support vertical position and "R_2" distance between bridge leaf pivot and cylinder rod support point. Geometrical parameters of presented bascule bridge mechanism shown in Fig.5 and Fig.7 are listed in Table 1.

Table 1. Geometrical Parameters

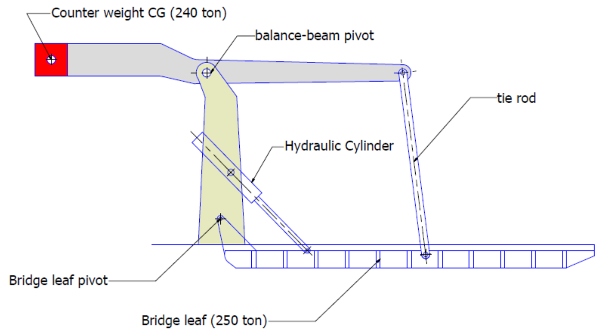
θ_0 (deg.)	r_1 (mm)	r_2 (mm)	r_3 (mm)	r_4 (mm)	$\emptyset_1$ (deg.)	d_1 (mm)	R_1 (mm)	$\emptyset_2$ (deg.)	d_2 (mm)	R_2 (mm)
84	9000	11900	8900	12800	76	6100	5180	78	2850	5900

Based on equation (9) and equation (10) the relation between bridge leaf opening angle "θ_2" and operating hydraulic cylinder length "l_1"in push arrangement is obtained and illustrated in Fig.8 (a) and based on equation (11) the relation between bridge leaf opening angle "θ_2" and operating hydraulic cylinder length "l_2"in pull arrangement is obtained and illustrated in Fig.8 (b). These relations are important in conceptual design stage for bridge operating hydraulic control system design and selection.

3.2 Bridge Mechanism Modeling



(a) Push arrangement

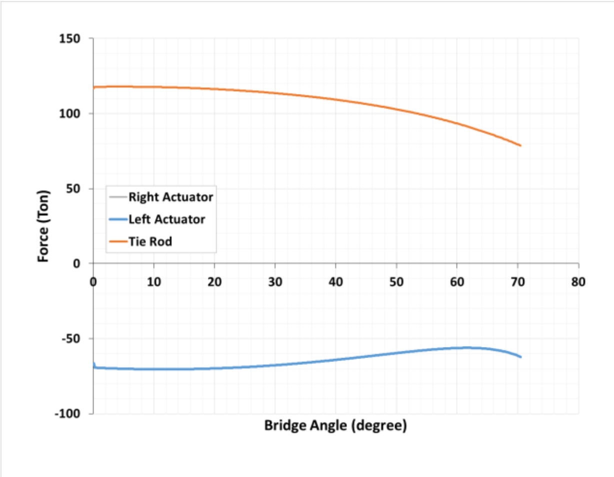


(b) Pull arrangement

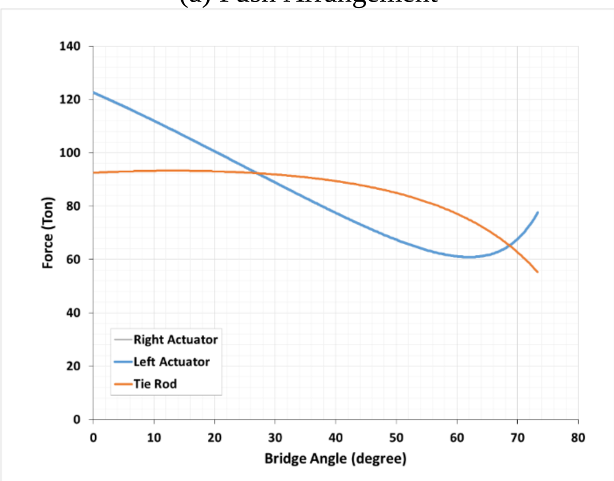
Fig. 9: Bascule bridge mechanism model

For the sake of comparative analysis of bascule bridge mechanism using hydraulic system arranged in both push and pull architectures , a 3D model of bridge system is created such that bridge leaf is 22m long and 15m wide and weighted 250 ton is attached to balance beam through two tie rods. Counter balance weight of 240 ton is attached to the balance beam. Fig.9 illustrates the bascule bridge mechanism model in both push and pull architectures.

Forces acting on tie rods and hydraulic cylinders (actuators) of the bridge mechanism during bridge leaf opening in both push and pull arrangement are illustrated in Fig.10.



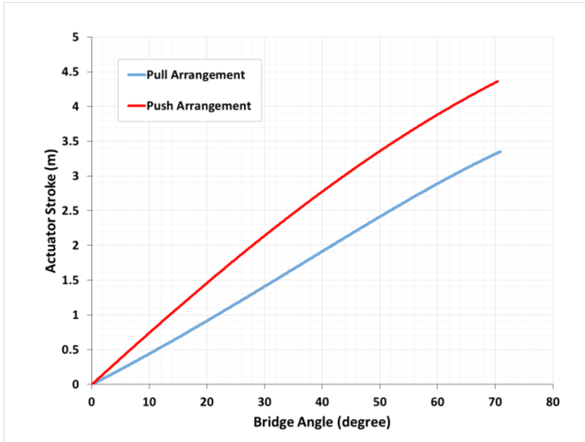
(a) Push Arrangement



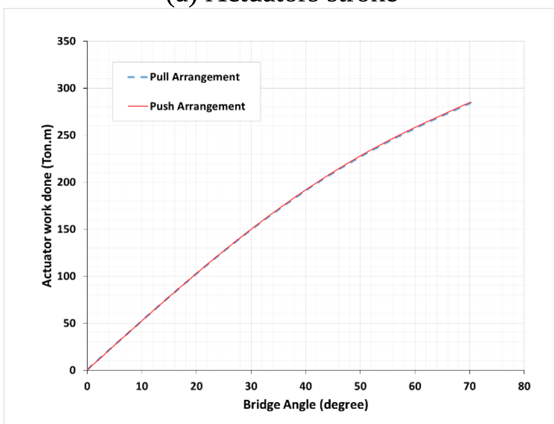
(b) Pull Arrangement

Fig. 10: Forces acting on tie rods

In push arrangement forces exerted by hydraulic cylinders is acting on balance-beam which rotates pulling the tie rods and hence bridge leaf open. In this case moment applied by balance beam counter balance and hydraulic cylinders acting on bridge leaf via the tie rods in tension while in the case of pull arrangement case the tie rod affected by tension force due to the effect of balance beam counter balance and compression force due to pulling action of the bridge leaf by the hydraulic cylinders. This explains the difference of tie rods forces shown in Fig.10 (a) and Fig.10 (b). This note can be stated as the first advantage of pull arrangement over push arrangement. Fig.10 shows that forces acting on both right and left actuators (cylinders) are behave same manner as the system explained by rigid body motion as mentioned before in the assumptions and they will appear as a single line in most of the coming results figures. Concerning forces required by actuators (hydraulic cylinders); Fig.10 shows significant difference between actuators forces in push and pull arrangement. This difference is due to distance between actuator and active pivot for each case and as a result both actuators has different stroke length for the bridge mechanism to set the bridge leaf to the opening position.



(a) Actuators stroke



(b) Work done by actuators

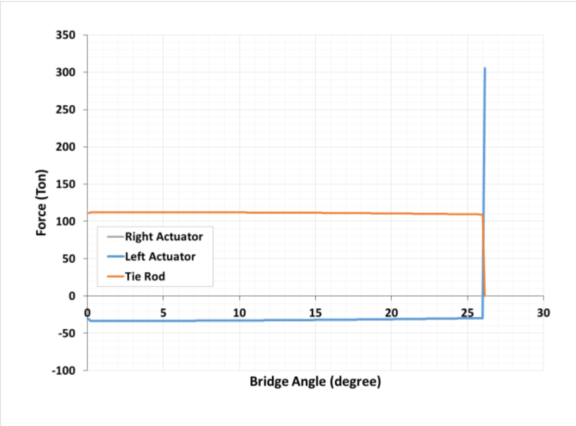
Fig. 11: Actuators configuration and work done to rotate bridge leaf

The relation between actuators stroke in both push and pull arrangement and bridge leaf opening angle is illustrated in Fig.11(a) in the other hand work done by each actuator in both push and pull arrangement is illustrated in Fig.11(b). As shown in Fig.11 (b) work done by hydraulic cylinders (Actuators) in both arrangement is nearly identical.

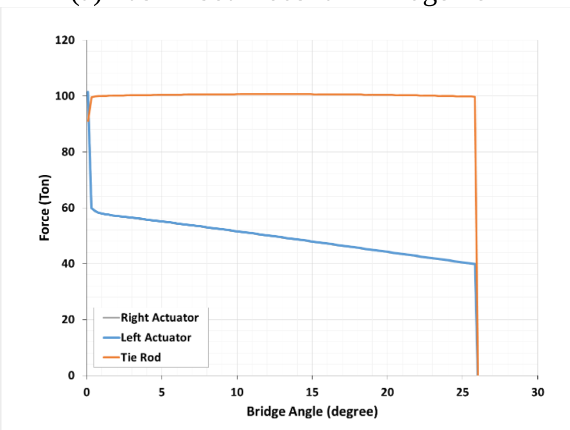
4 Discussion of Failure Scenarios

Some failure scenarios are introduced and behaviour of both push and pull arrangement mechanism architecture is discussed.

First scenario is that both tie rods fail and both actuators fail: in this case bridge leaf will fell as illustrated in Fig.14.



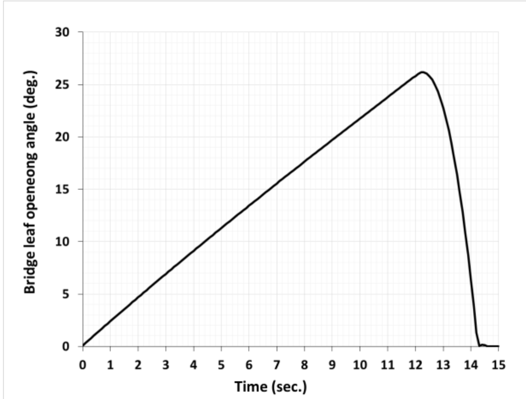
(a) Push – both rods fail- Bridge Fell



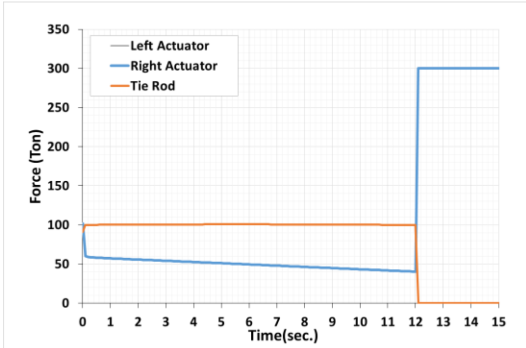
(b) Pull – both Rods and actuator fail – Bridge Fell

Fig. 14: Forces in first failure scenario

Second failure scenario is that both tie rods fail but actuators can withstand the jump applied load as shown in Fig.15. Fig.15 (a) illustrate bridge leaf opening with respect to time as the bridge mechanism operates. At angle 22^{o} tie rods fail and bridge leaf starts to close down to bridge span support. In this case if the system designed to withstand this load jump; bridge leaf will subjected to hydraulic actuators pull forces only and hydraulic system safety valves will blocking the cylinders at this pressure to insure save close to the bridge leaf avoiding sever damage.

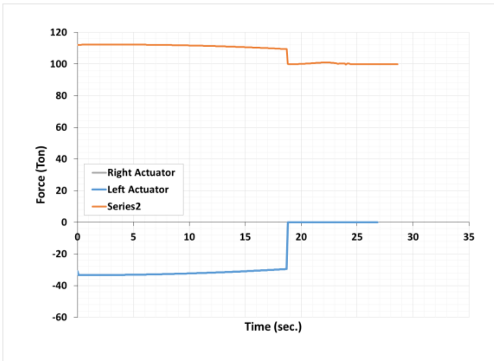


(a) Bridge leaf opening

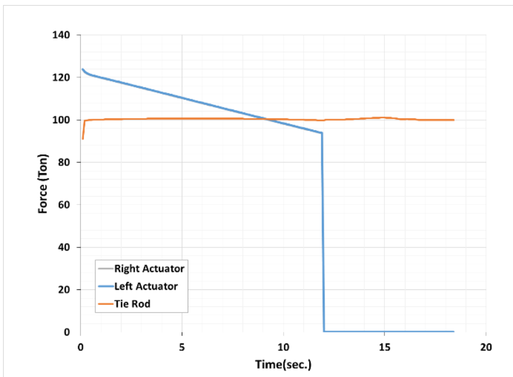


(b) Actuators and tie rods forces

Fig. 15: Second failure scenario



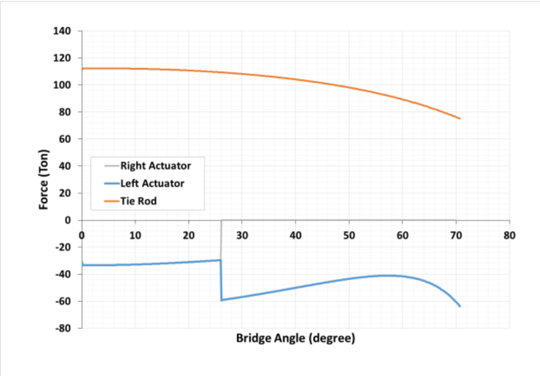
(a) Push – both actuator fail – Bridge Fell



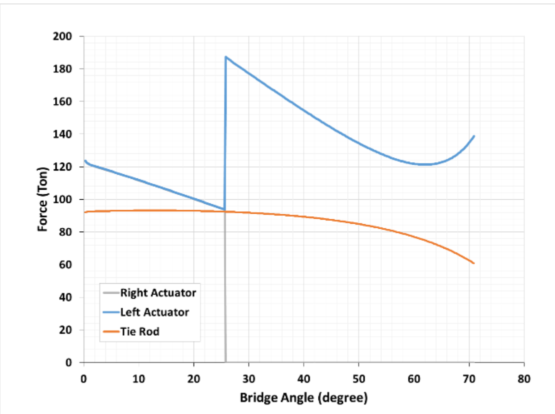
(b) Pull – both actuator fail – Bridge Fell

Fig. 16: Forces in third failure scenario

Third failure scenario is that both actuators fail while tie rods still active: As shown in Fig.16 during normal operation of bridge leaf opening and at angle of 26° hydraulic actuators fail and hence the bridge supported only by the counter balance moment acting on tie rod. As bridge leaf weight moment is higher than the counter balance moment; bridge leaf rotates back to the close position.



(a) Push– single actuator fails



(b) Pull – single actuator fails

Fig. 17: Forces in forth failure scenario

Forth failure scenario is that one of the hydraulic actuators fails while the other is still active along with tie rods. In this case a jump of actuator force is occurred as shown in Fig.17 (a) and Fig.17 (b) which illustrate the behavior of actuators load if failure of right actuator is introduced in both push and pull arrangement.

Failure of tie rod or hydraulic system may be occurred due to non-accurate design, low production quality control, improper selection of hydraulic system and extreme operation conditions that not considered in design stage. If such failure occurs during operation; bridge leaf may fall down striking bridge support and hence bridge sector may be damaged. A comparison of impact impulse of bridge leaf and bridge span support is carried out for the first three failure scenarios where bridge leaf fell and strike bridge span support. Results of impact impulse are illustrated in Fig.18.

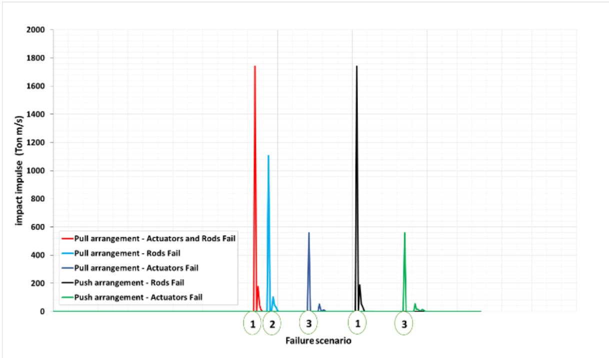
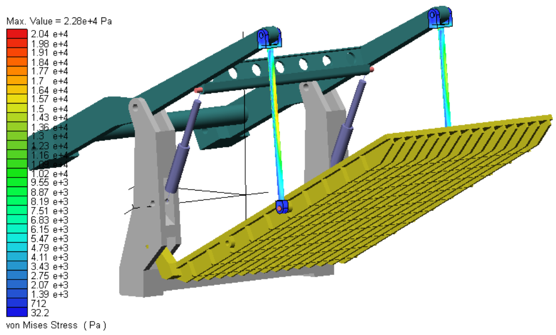


Fig. 18: Bridge leaf impact impulse for failure scenarios no. 1, 2 and 3

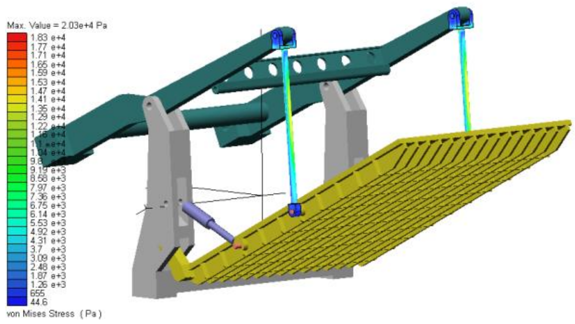
As shown in the figure; both push and pull arrangements shows similar impact impulse trend in the first and third failure scenario while pull arrangement shows interested behavior in the second failure scenario when tie rods fail and hydraulic system withstand the jump applied load.

5 Finite Element Results and Analysis

Stress analysis of both bascule bridge mechanism architecture is carried out using finite element modeling.



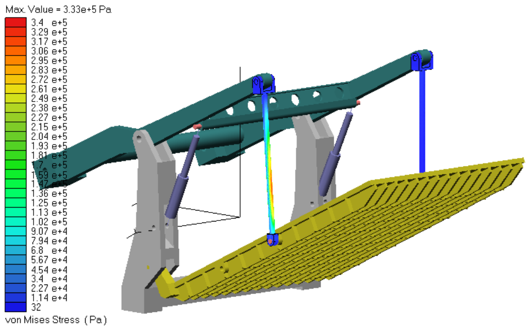
(a) Push Arrangement



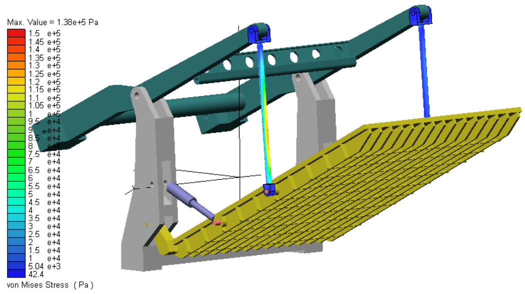
(b) Pull Arrangement

Fig. 12: Stress of Tie rods-both rods active

Von Misses stress distribution of tie rods considering both rods active is illustrated in Fig.12 and that of tie rods considering single rod active is illustrated in Fig.13 for both push and pull arrangements. The finite element results shows slight difference between the two architecture analysis cases in which both tie rods of the Bascule mechanism are active and transmit bridge span load to support beam structure as shown in Fig.12.



(a) Push Arrangement



(b) Pull Arrangement

Fig. 13: Stress of Tie rods- single rod active

While Left rod fail scenario is introduced during bridge opening procedure; finite element results shows significant difference between push and pull arrangement as stress acting on the active tie rod in pull arrangement is much lower than that in push arrangement as shown in Fig.13.

6 Conclusion

Stress distribution on tie rods shows lower stresses on pull arrangement rather than in push arrangement. Bridge leaf opening mechanism in pull arrangement show advantage that when tie rod fail during bridge leaf opening with caution design of the hydraulic control system bridge leaf return back to its horizontal position with relatively low impact impulse at bridge support.

As a conclusion bridge leaf mechanism in pull arrangement architecture provide redundant safety in design and operation with lower stress of operating structure components and this is an advantage over the push arrangement architecture one.

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Conflict of Interest

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