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Experimental and Numerical investigation of multi step Roll-bending process of IPB type beams

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Abstract: In this paper the multi-step roll-bending process of IPB type beams is investigated. For this purpose, simple and light weighted equipment with easy transportation has been designed and constructed. The results show that the product of this equipment is completely acceptable compared to pure rolling process while its cost and transportation is much less than massive rolling machine. The entire forming process has been also simulated by Finite Element Method using ABAQUS V.6.10.1 software. The simulated results indicate that the beam buckles during the forming process. Noteworthy is that the buckling mode and the maximum deflection value obtained from FEM are in very good agreement with experimental results. Therefore, suggested methods in order to solve the problem have been studied numerically by Finite Element Analysis instead of costly experimental study.

Keywords: Experimental Analysis; Roll Bending; Finite Element Analysis

1. Introduction

I shape curved beams are very applicable in the industry, such as tunnel construction, mining, bridge construction and etc. The most common beam bending method is rolling. In this method, the bending process is accomplished by crossing the beam through rollers. According to Fig. 1. rollers can be symmetrical or asymmetrical.

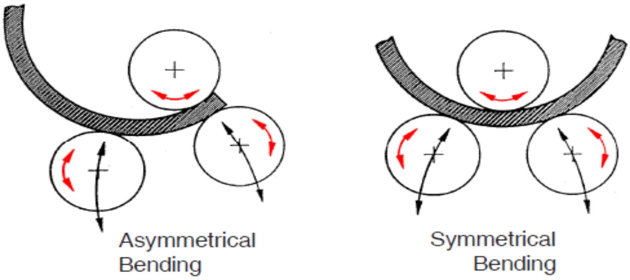

Fig. 1. Movements of rollers in symmetrical and asymmetrical profile bending [1]

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One of the advantages of rolling method is fine quality of its product as the rolling process is conducted continuously. Although this bending process costs a lot by rolling method but that is not the main disadvantage. The most important problem is that the rolling machine is massive and heavy. Therefore, the transportation of the equipment is difficult. Thus, it cannot be transported to a project site of digging tunnel in mountainous areas. On the other hand, the geometry dimension of a 12-meter curved beam is more than the allowable loading amount for a vehicle (maximum height is 4.5 meters) and consequently this makes the transportation to become very difficult.

This paper takes into account the bending of a 12-meter I shape beam by an innovative method in which the 12-meter I shape beam transforms into a semi-circle by multi process bending. The mentioned process has been also simulated by finite elements method in ABAQUS v.6.10.1 and the obtained results have been compared with experimental results, which show that they are in good agreement. For this purpose, very simple, light weighted and easy to transport equipment has been designed and constructed. The interesting point is that the final curved beam is very acceptable by this method comparing to rolling machine's product.

2. Multi step roll-bending method

The procedure of this new method has been illustrated in Fig. 2. As the figure shows, the upper rollers are fixed and only rotate around their axis while the lower roller is connected to one hydraulic cylinder which provides bending in the beam.

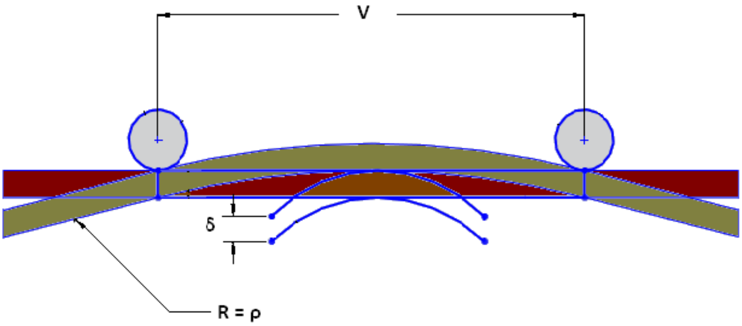

Fig. 2. Schematic view of multi-step roll-bending method

According to this method, at first a defined length of the beam is placed between upper and lower rollers and the bending process starts. Next other parts of the beam are placed in this area and the bending is continued. After several bending process, the entire beam transforms to a semi circle.

The curve radius of the curved beam depends on both the displacement of the lower roller along y axis and the distance between the two upper rollers. According to Fig. 2. if v is considered as the distance between the upper rollers and ρ is assumed as the curve radius of the bended beam, the displacement of the lower roller δ can be calculated from Eq. (1) as below [2]:

$$\delta = \rho - \sqrt{\rho^2 - (V/2)^2} \qquad (1)$$

The diagram of required displacement versus curve radius has been depicted in Fig. 3 for different distance between the upper rollers.

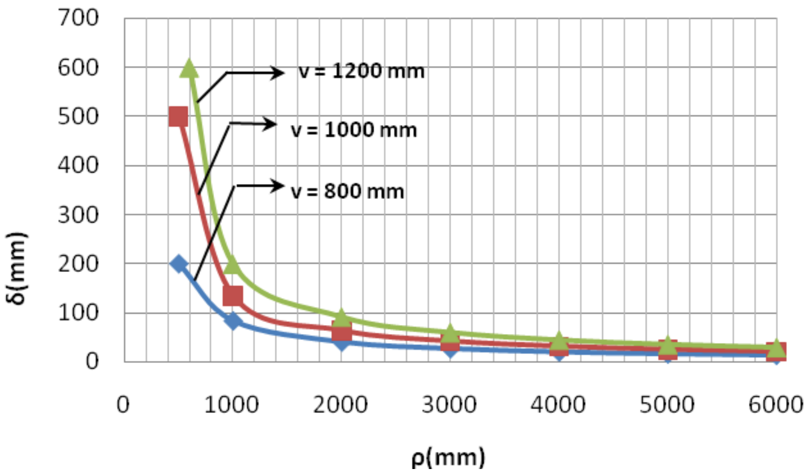

Fig. 3. Displacement of the lower roller versus curve radius for different distance between upper rollers

With the purpose of reaching to the desired curve radius equivalent to ρ = 3000 mm, it can be noticed that the lower roller has to be displaced δ =26.78 mm in terms of v = 800 mm for the distance of upper rollers. In addition, the lower roller has to be displaced more with the increase of the distance between upper rollers, in order to obtain a constant curve radius.

The stress distribution in the beam section in elastic and plastic region has to be according to Fig. 4. By reaching to the maximum yield stress, the plastic zone starts to become plastic from both section heads which are the places with maximum stress. The required force for bending has to be in a way that the beam section enters the plastic region as far as it is allowable. Considering this assumption that the vertical planes on the neutral axis befor loading remain vertical planes on neutral axis after loading, the curve radius can be calculated versus the maximum elastic stress according to Eq. (2) [3].

$$\rho = \frac{E\,(H + h)/2}{\sigma_{\max}} \qquad (2)$$

where E stands for elastic modulus, H is the height of the beam section and h is assumed as the thickness of the beam wing.

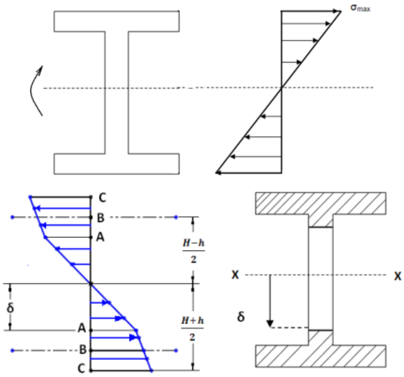

Fig. 4. The stress distribution curve in the beam section in cases of a) elastic and b) plastic

The diagram of curve radius versus maximum stress in elastic region has been depicted in Fig. 5.

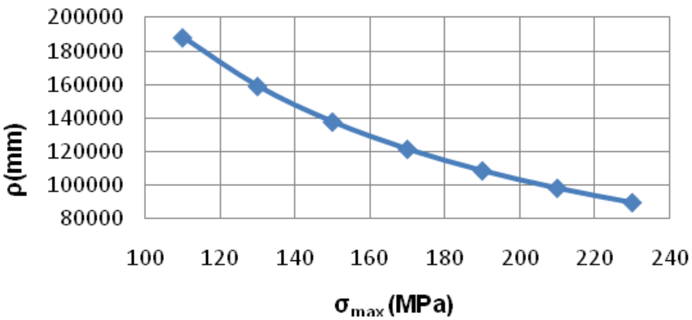

Fig. 5. Diagram of curve radius versus maximum stress in elastic region

Due to the fact that yield stress and ultimate stress of the studied beam made of St37 is equal to 235 and 630 Mpa respectively, therefore, according to Fig. 5. in order to reach to the desired curve radius which is ρ = 3000 mm, the required force during bending has to be such that the existing maximum stress in the beam would be greater than the yield stress and lower than the ultimate stress.

In elastic-plastic analysis of the mentioned beam, the relation between bending moment and stress is obtained by Equation 3 with the assumption that the plastic region starts from a distance equal to δ from neutral axis [4].

$$M = 2d\int_0^{\frac{H-h}{2}} \sigma y dy + 2D\int_{\frac{H-h}{2}}^{\delta} \sigma y dy + 2D\int_{\delta}^{\frac{H+h}{2}} \sigma y dy \qquad (3)$$

where D stands for the width of the beam section and d is the thickness of beam web.

With the consideration of linear stress distribution in the plastic region and with calculating the integration of Eq. (3), the curve radius diagram versus maximum stress in plastic region obtains according to Fig. 6.

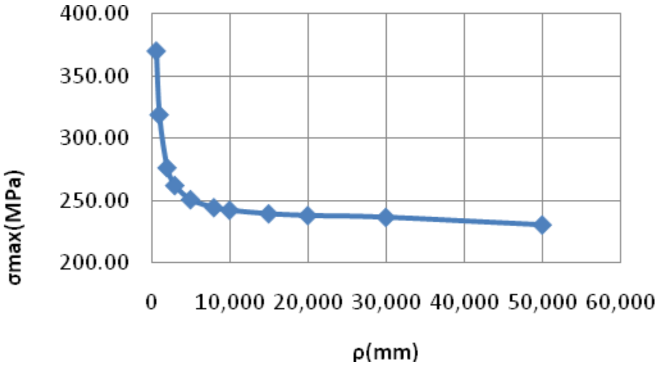

Fig. 6. Diagram of curve radius versus maximum stress in plastic region

As it can be observed, the maximum stress versus curve radius of ρ = 3000 mm is equal to $\sigma_{max} = 262.43\ MPa$, which is greater than the yield stress but lower than the ultimate stress.

3. Experimental analysis

Fig. 7. shows the multi-step roll-bending of IPB type beams machine. As it has been mentioned earlier, in this equipment the upper rollers are fixed and rotate only around their own axis. But the lower roller is connected to one hydraulic cylinder which provides bending in the beam.

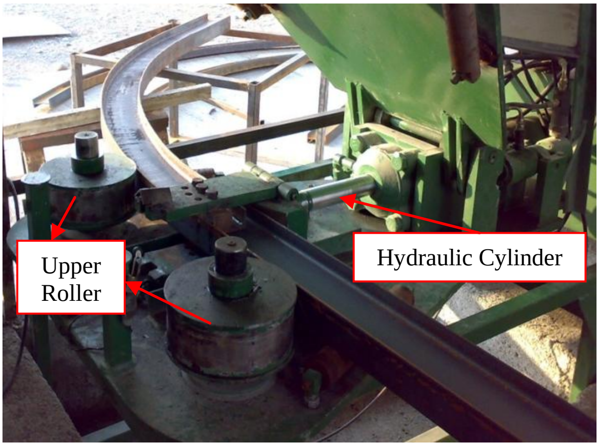

Fig. 7. Multi step roll-bending of IPB type beams machine

The notable point is that in initial experiments which were conducted by this equipment, beam web buckles during the bending process, as shown in Fig. 8. The reason is that beam web is under compression when the load is applied from the downside of the beam wing.

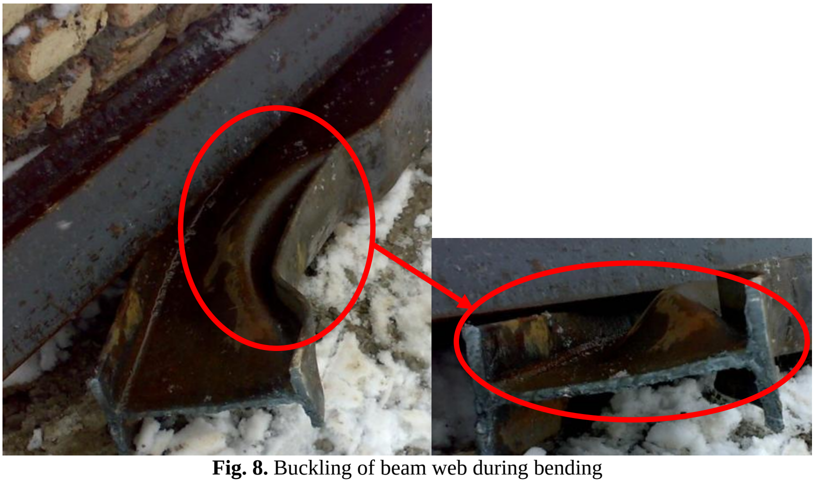

Fig. 8. Buckling of beam web during bending

In order to prevent such buckling, instead of applying the load just from downside of the beam wing which causes beam web to be under compression, it is sufficient to add two other pushers to the lower roller according to what Fig. 9. illustrates. Thereafter, the applied load for bending is also transformed to the upside of the beam wing, which makes beam web to be under tension. The problem is completely resolved by implementing these modifications.

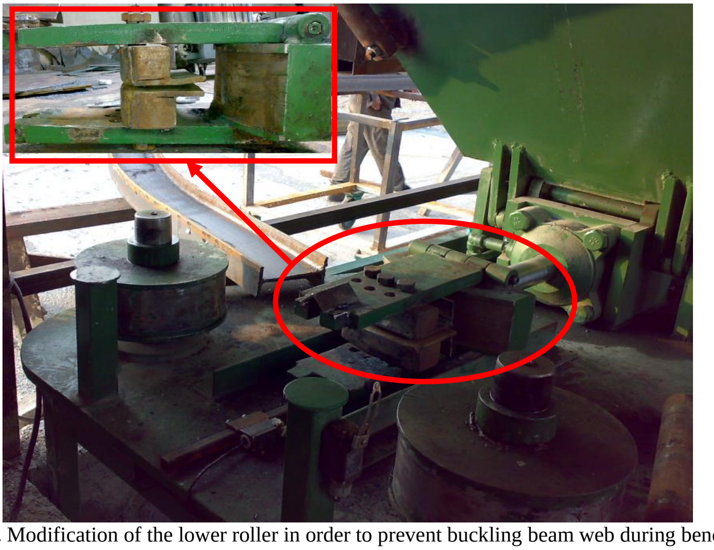

Fig. 9. Modification of the lower roller in order to prevent buckling beam web during bending

4. Numerical analysis

Fig. 10. depicts the geometry dimension of the studied problem. In this problem the rollers are modelled as rigid and in order to mesh the beam the first order shell elements S4R have been used.

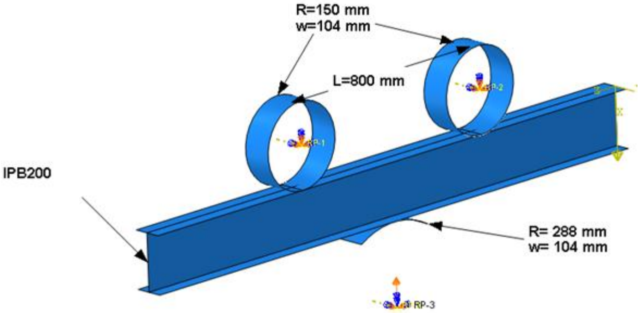

Fig. 10. Geometry dimensions of the studied problem

Between outer surfaces of the rollers and the beam, contact pairs with frictional coefficient of 0.2 have been considered. As it was mentioned before, the beam is made of St37 steel with the mechanical properties as given in Table 1. The upper rollers are fixed and rotate only around their own axis and the lower roller has displacement of 30 mm along *y* axis.

Table 1. Mechanical properties of St37 steel

Elastic modulus	E (MPa)	207000
Poisson ratio	ν	0.29
Yield stress	Sy (MPa)	235
Ultimate stress	Sut (MPa)	630
Density	ρ (kg/mm3)	7.85*10-6

Noteworthy is that if the lower roller is modelled as in the first case which means before the modification, according to Fig. 11. the simulated results would also represent the buckling of beam web during bending.

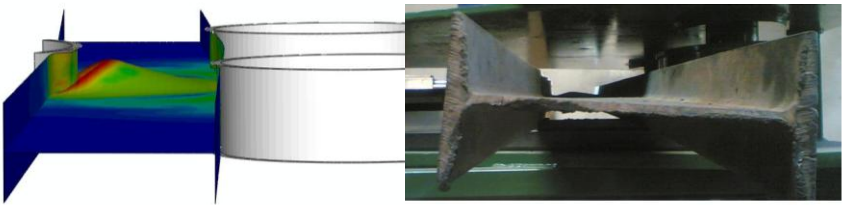

Fig. 11. Comparison between numerical and experimental results

In Table 2 the displacement of beam web along its vertical direction obtained from numerical results, has been compared by the measured amount in experiment. It can be observed that there is good correlation between numerical and experimental results.

Table 2: comparison between numerical and experimental results

Measured quantity	Experimental	Numerical	Error percentage
Maximum displacement of beam web in the buckled region	41mm	46.35mm	11.5%

It is necessary to mention that the buckling of beam web did not occur in the numerical simulation after the modification of the lower roller in modelling which is consistent with the fact.

5. Conclusion

This paper took into account the bending of a 12-meter I shape beam by an innovative method in which the 12-meter I shape beam transformed into a semi-circle by multi step roll-bending process. For this purpose, very simple, light weighted and easy to transport equipment was designed and constructed. The notable point was that beam web buckled in the initial experiments in which the problem was resolved with the modification of the lower roller. The final curved beam formed by this method is very acceptable comparing to the product of massive and heavy rolling machine with the difference that this new equipment can be transported easily to project sites. Eventually, the mentioned process was also simulated by finite elements method in ABAQUS v.6.10.1 and the obtained results were compared with experimental results, which showed that they are in good agreement.

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