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A Comparative Study of Force Prediction Models during Static Bending Stage for 3-Roller Cone Frustum Bending

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***Abstract*—**Conical sections and shells of metal plates manufactured by 3-roller conical bending process are widely used in the industries. The process is completed by first bending the metal plates statically and then dynamic roller bending sequentially. It is required to have an analytical model to get maximum bending force, for optimum design of the machine, for static bending stage. Analytical models assuming various stress conditions are considered and these analytical models are compared considering various parameters and reported in this paper. It is concluded from the study that for higher bottom roller inclination, the shear stress affects greatly to the static bending force whereas for lower bottom roller inclination it can be neglected.

***Keywords*—**Roller-bending, static-bending, stress-conditions, analytical-modeling.

I. INTRODUCTION

A long strip of metal is passed through consecutive sets of rollers or a roller stand in 3-roller cone frustum bending operation to obtain the desired cross sectional profile. The rollers of the bending machine can be arranged either horizontally or vertical with symmetrical or asymmetrical configuration. The cone frustum shells manufactured by passing metal plates through 3-roller bending machines are widely used in process industries. Diagram of 3-roller cone frustum bending operation is shown in Fig. 1.

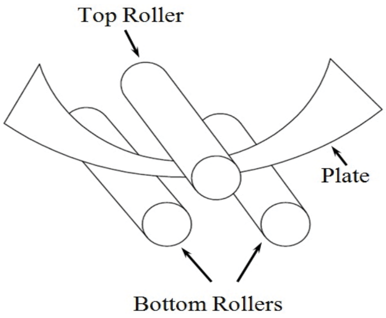

Fig. 1 Schematic Diagram of 3-roller cone frustum bending

3-roller cylindrical bending is having 2-dimensional stress pattern and forces, and hence mechanics involved during cylindrical bending is simple. During cone frustum bending using 3-roller conical bending, due to roller inclinations, the process involves 3-dimensional stress pattern and forces. It is difficult to simplify the 3-dimensional force pattern involved in conical bending. Hence, conical bending involves complex mechanics and it is difficult to analyze. Springback prediction models for the roller bending/forming of plates for cylindrical bending were developed with the assumption of single pass bending only [1]-[3]. Few researchers had worked on curve bending of the plates other than cylinder [4]-[6], whereas conical and elliptical structures have been extensively used in practice for the various structural applications. FEA is used for analysis of conical bending process by compatible rollers [7]. To study the effects of temperature on reaction forces, FEA has been used [8]. The reported FEA models have not been validated with experimental results. Hence, it cannot be used for prediction of the reaction forces over the rollers. Work related to machine setting parameters required for conical geometry for 3-roller bending has also been reported [9]. The conical bending process using 3-roller conical bending machine has been investigated considering the machine setting parameters for various cone geometries [10], [11].

During the static bending stage, the top roller of the 3-roller machine has to apply the force to bend the plate. If an analytical model of force prediction is available, it can be used for the estimation of the bending force required by the machine and the machine can be designed accordingly. Attempt for development of bending force prediction during static bending stage have been reported [12]. To develop the analytical model of force prediction, the external bending moments required to bend the plate has been equated with internal bending moment induced in the plate. As the stresses induced in the plates are 3-dimensional in nature, it can be formulated assuming the simplified stress conditions. Stress conditions can be simplified assuming three cases namely, i. Major stress along an axis only, ii. Principal stresses coincide with the normal axes, iii. Considering shear stresses along with the normal stresses. Considering these cases analytical models of bending force prediction for static bending stage have been developed and reported [13]-[15]. Comparison of analytical models for dynamic bending stage have been reported [16] but comparative study of analytical models for static bending stage have not been reported to the best of the knowledge of the authors. Hence, in this paper comparative study of analytical models for static bending stage has been carried out.

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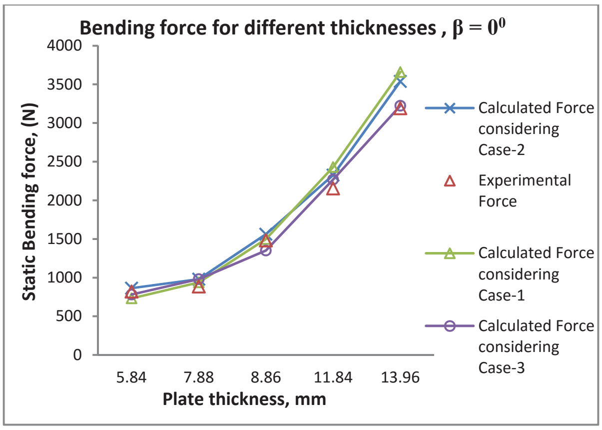
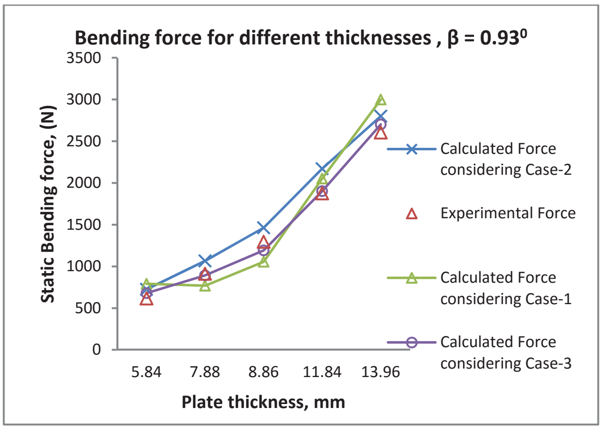
II. COMPARISON OF ANALYTICAL MODELS

Material property parameters and geometrical parameters involved during the static bending stage have been inserted and bending forces have been calculated for different stress conditions. Comparison of the analytical results considering three cases have been done by plotting them on the same graph with respect to plate thicknesses keeping the geometrical parameters, e.g. bottom roller inclination as constant. The graphs have been plotted considering five different bottom roller inclination viz. 0°, 0.93°, 1.86°, 2.79° and 3.71° as shown in Figs. 2 (a)-(e). Experimental bending force is also plotted along with the analytical results to check the accuracy of the different models as shown in Figs. 2 (a)-(e). Relative error of analytical results with respect to experimental results have been calculated and shown in Table I.



(a)



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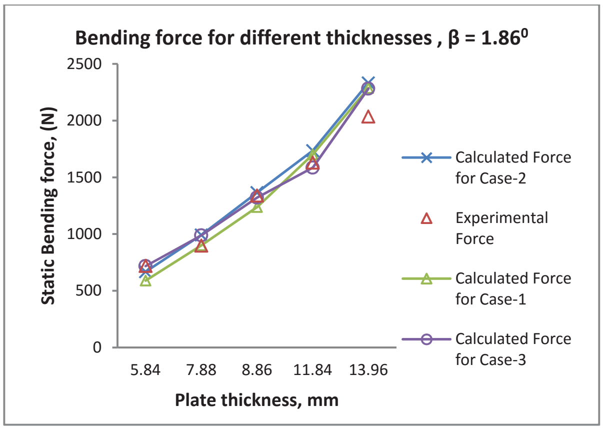

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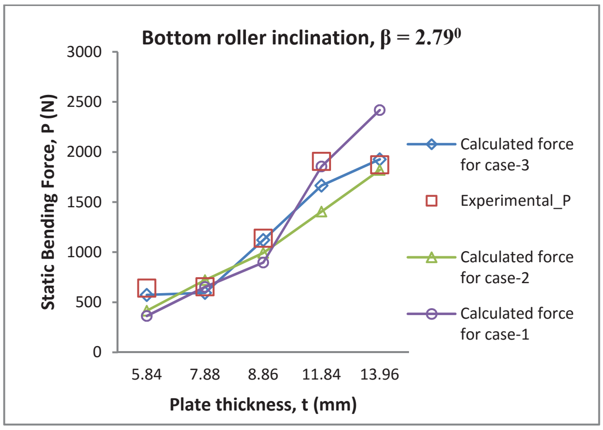

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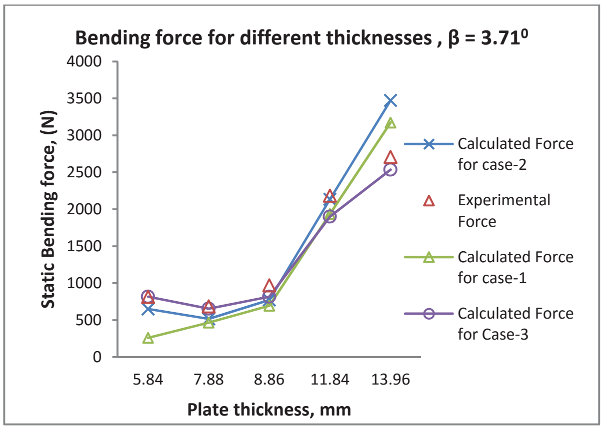

(e)

Fig. 2 Comparison of experimental and analytical Static bending force considering case-1, 2 & 3

As the thickness of the plate increase, force require to bend it will increase. The same can be observed from Figs. 2 (a)-(e) for all the three cases. The average error observed considering for stress condition with shear stresses, i.e. case-3 for all the given thicknesses ranges from 5% to 8% as can be seen in

Table I. Also maximum error for analytically calculated force with experimental result is 16% for case-3. Various assumptions were made during the derivation of the analytical models along with the stress conditions and hence these errors observed for prediction of the static bending forces [12].

It can be observed from Table I that the average error observed considering case 3 is very less as compared the errors observed for previous two cases. Considering the uncertainty of the process as well as uncertainty of various instruments used for the experimentation, the range of average error as well as maximum error that is observed in the third case is marginal. Hence the model can be used with marginal error for the prediction of the bending force during single pass 3-roller conical bending process. It is to be noted that as the bottom roller inclination increases the average error observed for the given thicknesses also increases, but it is marginal as compared to the increase in the average error for the first as well as the second case as can be seen in Table I.

Standard deviation for the force prediction is 1.1305 for case-3 is less as compared to 4.1852 for case - 2 and 8.3327 for case-3 (Table I). It can also be observed from Figs. 2 (a)-(e) that the analytical model considering case-3 gives better approximation as compared to the prediction by case-2 and case-1. This is because of the consideration of shear stresses in the derivation of the bending force model for the third case. As discussed earlier the shear stresses affect the bending force more in case of larger bottom roller inclination. In previous two cases, the shear stresses were neglected and because of that the errors observed were higher for higher bottom roller inclination.

To compare increment of the average error for the above mentioned three cases, they have been plotted on a bar chart as shown in Fig. 3. It can be observed from the bar chart in Fig. 3 that the average error increases as the bottom roller inclination increases. The reason for increase in the error, as bottom roller increases being the shear stress as discussed earlier. When the bottom roller inclination increases, resulting cone angle will be more. The bending planes will have more inclination with the bending axis when the cone angle is more. It induces higher shear stresses in the plate material during bending inclined planes as compared to parallel planes. Hence there will be more shear stresses as compared to the shear stresses for less cone angle. In first two cases the shear stresses are neglected. So for smaller bottom roller inclination i.e. for smaller cone angles the analytical results obtained will give smaller errors. The analytical model for first and second case will give larger errors for larger bottom roller inclination, as shear stresses are neglected. But in the third case, as the shear stress is considered for the analytical calculations, the analytical results obtained will give smaller errors even for higher values of bottom roller inclinations. Hence it can be concluded that the analytical model developed considering first two cases can be used for smaller values of bottom roller inclination while the analytical model developed considering third case, i.e. considering shear stresses can be used for prediction of bending force for higher values of bottom roller inclination with good accuracy.

TABLE I
ERROR IN PREDICTION OF STATIC BENDING FORCE FOR CASE-3 FOR DIFFERENT BOTTOM ROLLER INCLINATION

Thickness, t (mm) / Bottom roller inclination, β (degree)	5.84	7.88	8.86	11.84	13.96	Average Error for case -3 (%)	Average Error for case -2 (%)	Average Error for case-1 (%)
	Error (%)							
0	4.61	10.95	8.87	5.36	1.02	6.16	8.11	9.11
0.93	10.38	2.18	7.96	1.49	3.76	5.16	14.26	17.50
1.86	0.25	10.05	1.36	2.72	12.09	5.29	8.16	8.52
2.79	10.68	9.31	1.66	12.66	2.91	7.44	13.65	19.36
3.71	0.05	4.60	15.82	13.02	6.37	7.97	19.23	31.40
Standard Deviation						1.1305	4.1852	8.3327

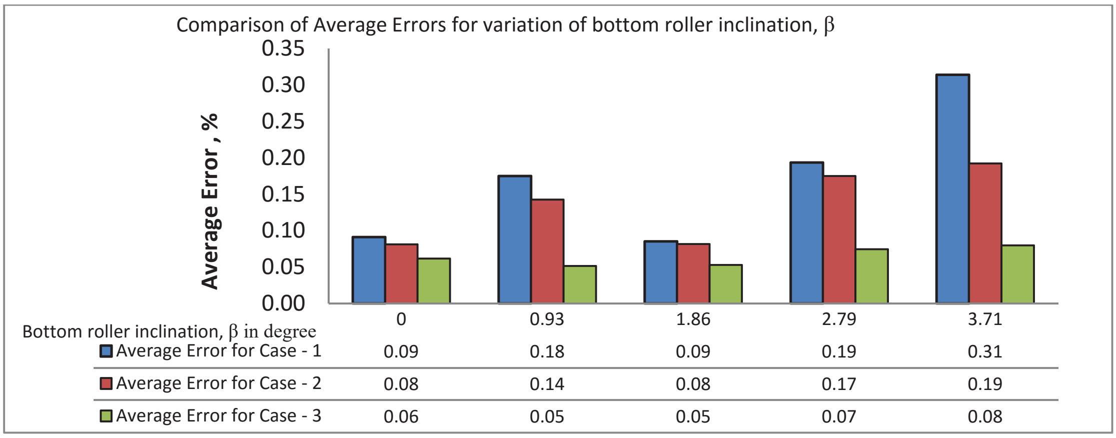

Fig. 3 Comparison of average errors observed in static bending force prediction considering various cases

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