Effects of residual stresses and shape deformities on failure of rollover protective structures

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Abstract. Rollover Protective Structures (ROPS) are manufactured typically from components that require forming such as pipe bending process. The manufacturing process creates residual stresses and shape deformities in the pipe structure. These parameters in turn may affect the strength of the pipe to bear the load during rollover. Conventional modeling does not capture the effects of residual stresses and shape irregularities in the pipe resulting from forming. A detailed analysis is therefore required to determine the significance of the manufacturing process on the strength of ROPS. Finite Element Method (FEM) is employed to simulate the bending process. Residual stress and deformation data from bending process analysis are used to further investigate failure of the structure under different loading conditions. The maximum load the structure can withstand, before it loses its stiffness, under a specific displacement is referred to here as failure load. Results revealed that there is a significant difference in the failure loads due to presence of bending process induced residual stresses and due to shape deformities. The model with the residual stresses and shape deformities has higher failure loads as compared to the conventional model. It also has been noted that residual stress is the main contributing factor to this increase in failure load. Parametric study was performed to investigate the effect of pipe wall thickness and radius of the formed bend on the failure loads.

1. Introduction
In order to improve operator safety, farm and mining vehicles have to be equipped with roll over protective structures (ROPS). In general design and testing of the ROPS, the structure is analyzed using finite element methods for sufficient stiffness and energy absorption before the loading causes the deflection to cross the limits specified by the standards [1]. However these results could be unrealistic considering the fact that the residual stresses created in the structure during the manufacturing process could produce significant impact [2]. So a simple model of a bent pipe ‘L’ shape is considered to study in detail the effect of these residual stresses on the failure loads under loading conditions similar to lateral and longitudinal loading of ROPS testing [1]. Finite element methods can satisfactorily capture the residual stresses created in a bending process [3]. Since the main objective was to determine the impact of the residual stresses concentrated in the bend, the standard loading conditions are slightly modified to meet the needs. The finite element package Abaqus/CAE 6.9-1 was used for the entire analysis of this study.

2. Analysis model
The analysis considered three cases as listed in table 1.
Table 1. Model cases used in the analysis.

| Case      | Residual Stresses | Shape Imperfections |
|-----------|-------------------|---------------------|
| Case – I  | No                | No                  |
| Case – II | No                | Yes                 |
| Case – III| Yes               | Yes                 |

The model used for Case-I is shown in figure 1. The bending process, shown in figure 2, is an unstretched bending process which produces moderate strains in the final model [4]. While Case-II model uses the shape at the end of bending process, Case-III includes that shape and the residual stress created in the bending process as well, and considers the spring back that occurs once the dies are removed.

Material: The material model used for the analysis is A500 Grade C, cold formed, carbon steel structural tubing. The true stress - true strain curve is constructed out of the engineering stress - engineering strain curve by assuming that the necking occurs at 21% elongation and the reduction in cross section at failure is 45%. The curve beyond the 21% strain is extrapolated using the above assumptions. Also a ductile damage model is constructed and included in the material properties with the damage occurring at 26% true strain. Ductile damage initiation and propagation functions of Abaqus are used to reproduce the material damage [5]. The assumed material property is as shown in figure 3.

Assumptions in Model: A few assumptions in the model are made to simplify the analysis. During the bending process the friction between the rollers and the pipe is assumed to be zero. The ends of the pipe are constrained as shown in figure 4. The nodes on the edge are coupled to a reference point at the center to ensure they do not lose their circularity during bending process. This simplifies the transfer of the model data from Abaqus/Explicit model for bending process to ROPS failure static load analysis model using Abaqus Standard solver. Abaqus/Explicit is a dynamic analysis procedure best suited for simulating forming operations. The spring back and failure load analysis however utilized Abaqus/Standard static equilibrium procedure.
Loading Conditions: A depiction of the lateral loading of ROPS is as shown in figure 5. Only half of the entire structure (an ‘L’ shaped pipe) is considered for this analysis. Also the chief concentration was on the bend of the pipe. The lateral loading on ROPS forces the bend near the direction of application of force to open up and the other to close. In Load-1 condition used in the analysis as shown in figure 6a, the ends are pushed together closing the bend and in Load-3 condition, as shown in figure 6b, the ends are pulled apart and the bend opens up.

![Figure 5. Lateral Loading on ROPS structure.](image)

![Figure 6a. Load-1 case-displacement causes the bend to close.](image)

![Figure 6b. Load-3 case-displacement; bend to open.](image)

ROPS longitudinal loading is shown in figure 7. The equivalent scenario in this analysis is shown in figure 8 (Load-2), which is a modification of the standard longitudinal loading on ROPS used for estimating the failure load of the bend. Here the tube is mainly subjected to twist mode.

![Figure 7. Longitudinal loading on ROPS structure.](image)

![Figure 8. Loading condition (Load-2).](image)

The point of application of the load is the center of the pipe end. The center point is coupled to the edge restricting any local deformities of the edge. The other end of the pipe is similarly coupled to a center point where the pipe is pivoted or fixed based upon the loading condition. The load cases are analyzed in detail for the model with the dimensions shown in figure 9.

![Figure 9. Model dimensions.](image)

![Figure 10. FR vs. displacement for Load-1.](image)

3. Results
Load-1 Case: The Load-1 condition is shown in figure 6a. Here the point of load application is pulled with a constant displacement until instability is realized by drop in reaction load or instability of the structure as it exhibits its inability to support the loading condition. Load-1 is applied to all the three
cases (Case-I, II & III) and the reaction force (R_F) at the displaced point is shown in figure 10. As seen from the graph in figure 10, Case-III is much stiffer than Case-I and Case-II. Case-III showed a 39% higher failure load than the other two cases. Moreover the failure load was reached at a shorter displacement compared to Case-I and Case-II. Case-II showed a little lower failure load compared to Case-I, but both had similar load - displacement profile. This clearly indicates that residual stress is the major contributing factor for the higher failure load in Case-III and not the shape deformities.

In Case-I the failure occurred mainly at the inner surface of the bend, figure 11 where the stress concentration was very high. In Case-II, the shape change, from perfect circular cross section to slight flattening at the sides during bending process, caused stress concentration at the sides and subsequently failure at the sides as well, and resulted in lower failure load, figure 12. Failure is depicted by strain exceeding the 26% limit, with elements losing their stiffness as was shown in the material model.

![Figure 11. PEEQ of Case-I under Load-1.](image1)

In Case-III, when the failure load occurred the strains in the model never exceeded the failure strain of 26%. So the structure first buckled under loading, and it then progressed to damage point at the outer surface of the bend. Failure occurred at the outer surface of the bend as shown in figure 13. As seen from figure 14, end of the bending process, the outer surface had a positive strain and hence compressive residual stresses. So stretching along the bending direction required a higher load to overcome the residual stresses. Once the material starts yielding under load the strain further increases and causes the damage to progress faster thus failing at a lower displacement than the other cases, figure 10. It was noted that Case-III reached the failure load after 1.64 cm of displacement while Case-I reached the failure load after 2.34 cm, 30% lower displacement than case of stress-free perfect cross section.

![Figure 12. PEEQ of Case-II under Load-1.](image2)

![Figure 13. PEEQ of Case III under Load-1.](image3)

![Figure 14. Case III under Load-1.](image4)

It has been reported [2, 6, 7] that the FEA results showed a little lower failure loads and a little higher displacement than actual ROPS testing, at failure. Thus Case-III can be assumed to be a more realistic model, relative to the other two cases.
Load-2 Case: The Load-2 condition is shown in figure 8. Here the point of load application is displaced with a specified rotational displacement. This Load-2 scenario is applied to all the three cases (Case-I, II & III), and the reaction moment (M_R) at the point is monitored as in figure 15.

![Figure 15. Reaction moment (M_R) Load-2.](image)

Again, as seen in the previous Load-1 condition, Case-III provides a higher resistance to the twist loading as compared to the stress-free models, Case-I and Case-II. This again proves that residual stresses play a key role in causing a 20% difference in failure load. Case-I and Case-II had inelastic buckling at about 7% strain, and then they progress to ductile failure. Both cases had failure at the same location, shown in figure 16. Case-I and Case-II had similar failure pattern but had small variation in the failure moment due to the shape deformities in Case-II.

![Figure 16. PEEQ of Case-I under Load-2.](image)

However, Case-III did not fail at the bend (as shown in figure 17) but instead buckled near the bend, and it resulted in higher reactive moment resistance; huge rotational displacement ensued before failure was reached. Since the 26% plastic strain damage limit was never reached, the failure mode here was buckling instead of plastic failure. As seen from figure 18 the residual stresses are concentrated at the bend, Case III. The failure load at the bend region was higher because of the residual stresses and consequently the higher yield strength. Buckling occurred near the bend instead of the bend where the material strength is lower. Since Case-III showed a failure mode different from that of Case-I and Case-II, and since the failure did not occur at the bend, a comparison of load vs. rotational displacement among the cases, as shown in figure 15, is not justified. But it can be said with confidence that Case-III has higher failure loads than the other two cases, if one were not to identify type or mode of failure.

Load-3 Case: Load-3 condition is shown in figure 6b. Load-3 acts to open the bend and the reaction force (F_R) indicating the material resistance is monitored and reported in figure 19.

![Figure 17. PEEQ of Case-III under Load-2.](image)

![Figure 18. Mises stress distribution of Case-III.](image)
Figure 19. Reaction Force ($F_R$) vs. Displacement.

Analyzing this load case in detail shows that Case-III exhibits a higher reactive force but fails at a very low displacement compared to the other two cases. In the other two cases, the bend continues to open to the fullest extent as shown in figure 20 of Case-I. Thus the failure load of Cases I and II is equivalent of a straight pipe subjected to a uniaxial tensile pull under axial limit load. Case-II shows a similar behavior but as seen from figure 19 Case-II undergoes a lower displacement even though the loads are almost the same. The midsection of the pipe as highlighted in figure 21 was the region subjected to the bending process. This region showed a reduction in cross section area during loading in comparison to the rest of the pipe. Case-I had a uniform reduction in cross area throughout and hence Case-II reached failure load at lower displacement than Case-I.

Figure 20. PEEQ, Load-3 in Case-I.

Case-III, as shown in figure 20, failed at a lower displacement. The outer surface of the bend in Case-III had positive strain due to stretching during the bending process as shown in figure 22. When Load-3 is applied these elements are stretched further in the same direction and damage strain was reached at a lower displacement than the other two cases. Though the failure occurred at a lower displacement the reactive force was slightly higher than other two cases for the same displacement (around 8.5 cm). The reason for the high reactive force is the compressive residual stresses in the bend region. Figure 23 shows the PEEQ at instability for Case-III. ROPS design and analysis takes into account the deflection limit which is the maximum displacement the structure can undergo before it interferes with operator safety. Conventional design and analysis do not consider residual stresses in the structure. It should be noted that if the deflection limit considered in conventional design and analysis is not properly chosen there is a chance that a false peak load value would be achieved as a result. For example if from the graph on figure 19 a deflection limit of 12 cm is chosen for a ROPS then one would be overestimating the failure load and failure displacement if residual stresses and deformities were not included.
4. Parametric study

Thickness of Pipe: Thickness of the pipe is varied, and the failure load under each loading condition and under each case was recorded. The trend with varying thickness is observed to be linear under each loading condition and is shown in figures 24, 25 & 26.

Radius of Bend: The radius of bend considered for the thickness analyses and for the general study was 3.5x radius of the pipe. For bend radius smaller than that, the model had strains exceeding the failure limits in bending process as shown in figure 27. Therefore, lower bend radius was not entertained.

Figure 23. PEEQ- Load-3 in Case-III.

Figure 24. Failure load vs. thickness under Load-1.

Figure 25. Failure load vs. thickness- Load -2.

Figure 26. Failure load vs. thickness- Load -3.

Figure 27. PEEQ showing failure at the bend.

Figure 28. Failure load vs. bend radius, Load-1.

Figure 28 show that the Load-1 case has an almost linear response to the radius of bend. As seen from figure 29 the load for Case-III remains almost a constant for all different bend radii. This is due
to the fact that Case-III has buckling behavior for failure and since the cross section area of the pipe remains a constant, the buckling load remains the same.

Figure 30 shows that for Case-I and Case-II the failure load remains almost a constant throughout the different bend radii for Load-3 situation. As seen from figure 20 and figure 21 failure in these cases is equivalent to subjecting a straight pipe to tension and hence there is no variation when the bend radius is changed. Case-III, due to the residual stresses, showed significantly less loads. But as the radius of the bend increased, the residual stresses and strains dropped causing the failure load to approach that of Case I and Case II, figure 30.

**Figure 29.** Failure load vs. bend radius- Load-2.  
**Figure 30.** Failure load vs. bend radius- Load-3.

5. Summary/Conclusions
As seen from the above results, it is clearly evident that the residual stresses are significant in determining the failure load and deflection limits for the ROPS structure. For the same lateral loads the deflection limit for the model with residual stresses could be less by as much as 40% as seen from Figures10 &20. The above analysis is limited to a particular material model, and the behavior might be different under different materials having larger or smaller ductility. If a different bending process is used then the residual stresses and the results may vary. This study did not attempt to include residual stresses present due to the manufacturing of the straight pipe.

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