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Investigation of Manufacturing Residual Stresses in Cold Formed Truck Frame Rail Sections

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ABSTRACT
Series of manufacturing processes such as coiling-uncoiling, cold forming and hole cutting processes involved in the making of truck frame rail sections leave certain amount of manufacturing imperfections into the frame rail. As the manufacturing imperfections in the form of residual stresses play a significant role in determining the dynamic structural behavior of truck frame rail members, a careful assessment of residual stresses resulting from coiling-uncoiling and cold forming processes is needed. In the present investigation, non-linear Finite Element (FE) simulation of coiling-uncoiling and cold forming processes were carried out and the resulting residual stresses in frame rail corner, flat web and flange sections were compared with the experimentally measured residual stress values using X-ray diffraction technique. It is observed that in corner sections, the numerically predicted residual stresses are in close agreement with the experimentally measured residual stresses in forming (transverse) direction. In the direction perpendicular to forming (longitudinal direction), while the trends of numerical and experimental residual stresses are observed to follow the same pattern, some deviation in stress values are observed in the inner half of the corner sections. As the coiling-uncoiling process is the main cause for the residual stress presence in flat web and flange sections, the computed coiling-uncoiling residual stresses in longitudinal directions are compared with experimentally measured residual stresses in frame web sections and the trends are observed to be in good agreement. Whereas the magnitudes of coiling-uncoiling residual stresses in transverse direction are found to be very low and considered to be insignificant for the comparative analysis. These residual stresses along with corresponding equivalent plastic strains and virgin material properties in terms of stress-strain relationships can be considered as initial conditions for the accurate prediction of truck frame rail fatigue behavior.
Keywords - coiling-uncoiling, cold forming, plastic strain, residual Stress, Truck frame rail, x-ray diffraction.

I. INTRODUCTION

The increasing demand for improved vehicle performance and fuel efficiency have forced commercial vehicle manufacturers to look into finer design aspects in order to reduce vehicle weight and at the same time improve the life of vehicle systems. While the availability of high speed computing hardware and finite element) simulation tools support the designers with all virtual test simulations being carried out in the early design stage, they often ignore the effect of manufacturing process induced variations and tend to use only the virgin material properties in their numerical models to predict the mechanical behavior of vehicle structures such as frame rails.

The use of virgin material properties in numerical simulations would not replicate the actual structural behavior of frame rail sections. Normally, the frame rails are subjected to number of manufacturing processes such as coiling-uncoiling, cold forming and hole cutting processes before attaining its final shape, which invariably modify the frame rail material properties and its mechanical behaviour. Since all these manufacturing processes leave some amount of residual stresses in frame rail sections due to excessive cold working, based on its magnitude and direction they have serious influence on its overall structural behavior. In order to consider these residual stresses and modified material properties as initial conditions for further numerical analysis, a thorough understanding of all the processes is needed.

Although there were no specific literatures available pertaining to the assessment of residual stresses in automotive frame rail structures, some experimental studies were found on cold formed steel sections employed in general steel structural applications. Quach [1] and Moen et al. [2] have attempted to quantify the residual stresses resulting from coiling-uncoiling process in cold formed carbon steel sections through finite element and analytical models. While Weng and White [3, 4] have measured surface residual stresses and through thickness residual stresses on thick cold bent steel plates using sectional method. It was reported that through thickness residual stress distribution was zigzag type and the maximum residual stress either occurs at inside surface of the bend or near the neutral surface of the plate.

Longitudinal residual stresses in press-braked and roll formed carbon steel channel sections were measured using strip-sectioning method by Batista and Rodrigues [5]. Similar approach was used to measure residual stresses in longitudinal direction of cold formed carbon steel sections by Weng and Peckoz [6] and in stainless steel square hollow sections by Young & Lui [7]. Key and Hancock [8] have showed complex variation of through thickness residual stress measured in thick cold rolled square hollow sections. A recent experimental work concerning X-ray diffraction measurements on square hollow sections were published by Li et al [9] showing variation of through-thickness residual stresses as bi-linear in both transverse and longitudinal directions. Yet, the experimental methods are not the only possibility of residual stress determination, there are analytical and numerical models [10, 11] conveniently used to predict the residual stress distribution in cold formed sections.

All these studies found in literature gave focus on static steel column structures and the effect of manufacturing processes on their column buckling behavior. There were no specific literatures found in the area of truck frame rail structures, which considers the effect of manufacturing processes on the dynamic fatigue behavior of frame rails. Through this work, an attempt was made to investigate the residual stresses and the associated plastic strains resulting from coiling-uncoiling and press forming processes through numerical simulations and compared the numerically predicted residual stresses with the experimentally measured residual stresses in truck frame rail sections.

1.1 Frame Material Properties

The frame rail material chosen for this study is BSK46, a widely used micro alloyed carbon steel in truck frame rails with chemical composition of *C* - 1.4%, *Mn* - 0.03%, *Nb* - 0.05%, *P* - 0.03%, *S* - 0.1% and *Si* - 0.03%. The mechanical properties of BSK46 material in terms of nominal stress-strain curve that gives Young's modulus of the material *E* - 210 *GPa* and Yield strength σ_y - 460 *MPa* is as shown in Fig. 1.

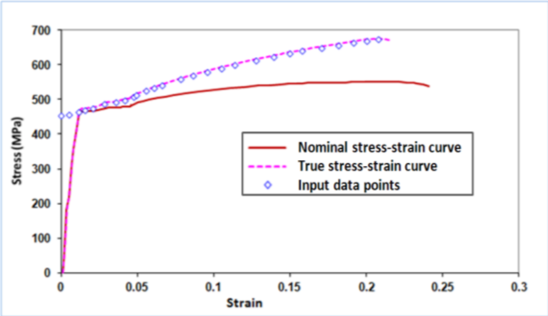

Fig.1. BSK46 material properties

The Poisson ratio measured is *ν* - 0.29. As the material non-linearity requires true stress-logarithmic plastic strain curve, it was derived from nominal stress-strain data up to the ultimate point and input data points were generated for numerical analysis.

1.2 Frame Section Dimensions

Fig. 2 depicts the sectional dimensions of frame rail sections chosen for numerical and experimental investigations in this work.

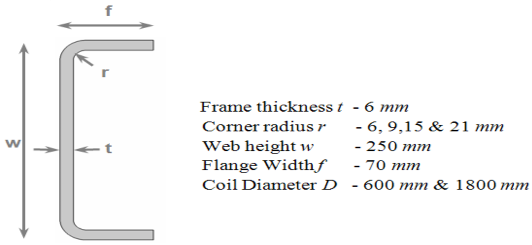

Fig. 2. Frame section dimensions

The dimensions *w*, *f* and *t* denote web height, flange width and thickness of frame rail sections respectively. While *D* is diameter of coil at which the steel sheet is extracted for frame rail section and *r* is inner radius of corner section.

II. COILING-UNCOILING SIMULATION

The steel sheets are normally transported as compact coils from steel mills to frame rail manufacturers. The coils received at frame rail manufacturing locations are first uncoiled and then subjected to cold forming process to attain final shape of the frame rail sections. These steel sheets prior to coiling in steel mill is normally subjected to annealing process, hence the residual stress state in steel sheet before the cold forming processes is mainly due to the coiling-uncoiling process the sheet undergoes. In order to capture these residual stresses and associated equivalent plastic strains, the coiling-uncoiling process is simulated in Finite Element (FE) environment. The input data points from non-linear strain hardened material properties of BSK46 steel grade considered for the FE simulation is shown in Fig. 1. In order to capture the non-linear through thickness residual stresses more accurately in BSK46 grade steel sheets of 6 *mm* thickness, a minimum of 16 layers CPE4R elements (which are 2D plane strain 4 noded elements with reduced integration and hour glass control for controlling deformation of elements during sudden loading) were chosen through the thickness and the final mesh size is arrived. Also for capturing the exact coil diameter, analytical rigid surface of equivalent diameter is modeled and surface contact pairs available in ABAQUS [12] are used to define contact between the sheet blank and the analytical rigid surface during the first step of coiling simulation. In this step, one end of the steel strip is fixed and the other end of the steel blank is pulled towards the analytical rigid surface with required displacement load in such a way that the steel blank takes the shape of analytical rigid surface, representing the actual coil diameter.

In the second step, the uncoiling process is simulated by reverse bending of steel blank to the initial zero curvature with required displacement load defined in the opposite direction. During the uncoiling process, the surface contact defined in the previous step is deactivated in order to simulate the uncoiling process more closely. At the end, a spring back analysis is performed in order to capture the presence of any residual curvature as the steel blank coming out from uncoiling machine is free from all the constraints imposed earlier. The simulation sequence captured during coiling-uncoiling process is depicted pictorially in Fig. 3.

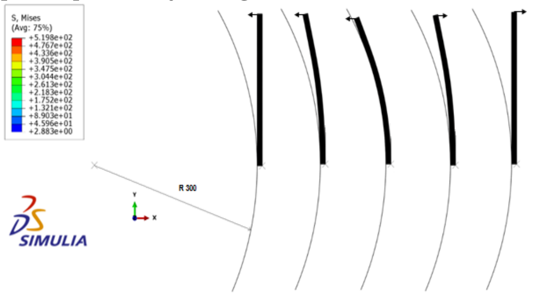

Fig. 3 Sequence of FE simulation steps in coiling-uncoiling process

The through-thickness residual stresses in longitudinal and transverse directions of frame rail web and flange sections obtained through FE simulation from various coil diameter locations due to coiling-uncoiling processes (as they are unaffected by cold forming process) are shown in Fig. 4 and 5. It is very important to note that as a manufacturing practice, the inner surface of steel coil becomes the outer surface of frame rail section and the outer surface of steel coil becomes the inner surface of frame rail sections during the making of frame rail sections.

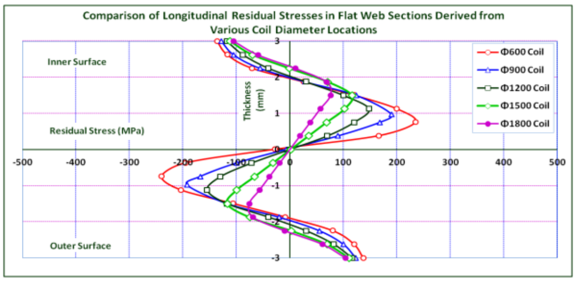

Fig. 4 Longitudinal through-thickness residual stresses in flat web sections derived from various coil diameter locations

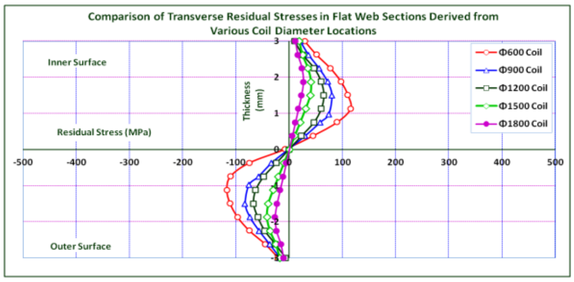

Fig. 5 Transverse through-thickness residual stresses in flat web sections derived from various coil diameter locations

From the figures, it is observed that the coiling-uncoiling residual stresses in longitudinal directions are predominant in frame web and flange sections and it increases with decrease in coil diameter. Among the stress values observed through the thickness, the outer surface longitudinal tensile residual stress plays a significant role in deciding dynamic fatigue cracking behavior of truck frame rail web and flange sections, subjected to extreme road operating conditions.

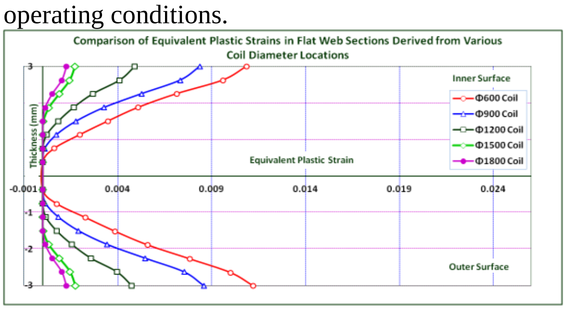

Fig. 6 Through-thickness equivalent plastic strains in flat web sections derived from various coil diameter locations

Similarly, through-thickness equivalent plastic strains due to coiling-uncoiling process on frame rail flat web sections derived from various coil diameter locations were calculated using FE simulation and depicted in Fig. 6. From the figure, it is observed that there are no plastic strains in the elastic core area. As the coil diameter increases, the elastic core thickness also increases with subsequent reduction in plastic strain.

III. PRESS FORMING SIMULATION

Among the three cold forming processes such as roll forming, angle braking and press forming process employed for making truck frame rail sections, the press forming process that helps to obtain final desired shape in a single pressing process is considered for the simulation study in this work. The sequence of steps involved in a typical press forming simulation is described pictorially in Fig. 7. In the finite element model, the analytical surfaces of punch, die and blank support were modeled by capturing the required outer section dimensions physically. The steel blank of 6 *mm* thick was modeled with 2-D plane strain 4 noded CPE4R element as it can handle both large strains and rotations. The interaction between punch & steel blank, die & steel blank and support & steel blank were modeled with surface contact pairs available in ABAQUS.

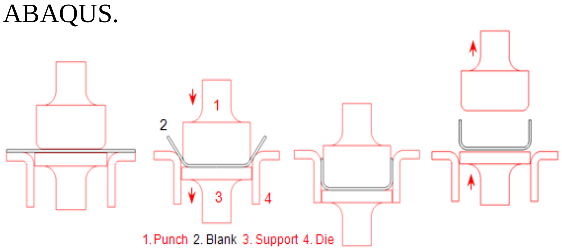

Fig. 7. Truck frame rail press forming process steps

Both geometrical and material non-linearities were considered in the numerical analysis. In order to replicate the physical loading conditions in the forming simulation, the die maintained in a fixed position and the tool along with support are moved (with a support load of 40 *kN* acting in direction opposite to tool motion) to required forming depth during the press forming process. Modeling of steel blank with 16 layers of CPE4R elements through the thickness helps to capture the varying through-thickness residual stresses very accurately. FE simulation was carried out for various frame sections with corner radius to thickness (*r/t*) ratios of 1, 1.5, 2.5 and 3.5 by changing tool and die section dimensions in FE models.

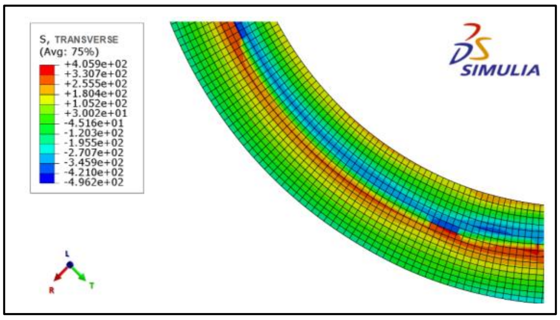

Fig. 8. Typical transverse residual stress contour plot in corner section with (r/t) ratio - 3.5

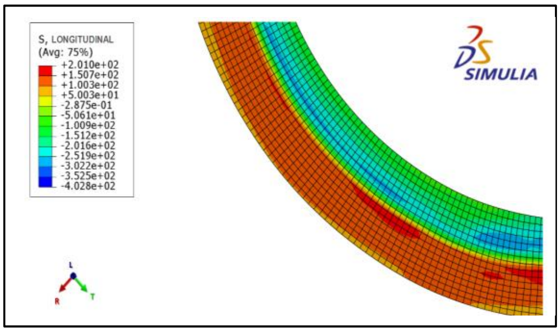

Fig. 9. Typical longitudinal residual stress contour plot in corner section with (r/t) ratio - 3.5

Typical contour residual stress plots obtained in transverse and longitudinal directions of a frame rail section corner with (*r/t*) ratio of 3.5 and BSK46 grade steel material are shown in Fig. 8 and 9 respectively. The through thickness transverse and longitudinal residual stresses obtained from non-linear finite element simulation for varying corner radius to thickness (*r/t*) ratios are shown in Fig. 10 and 11 respectively.

From the figures, it is observed that the change in direction of residual stresses doesn't occur exactly on the mid-surface but at a section slightly away from mid-surface of the steel sheet. The section at which the residual stress changes its direction is the new location of neutral axis for the corner section. It could also be observed that the shift in neutral axis from mid-surface for higher corner radius to thickness (*r/t*) ratios is minimum and for lower corner radius to thickness (*r/t*) ratios it is observed to be maximum. There exists a corner radius to thickness ratio (*r/t* >8), beyond which the shift in neutral axis is almost zero and these corner sections are known as long radius corner sections.

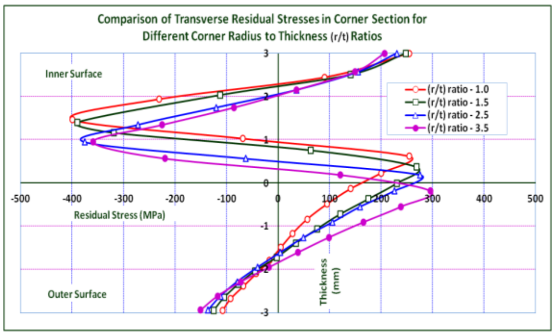

Fig. 10 Transverse through-thickness residual stresses in corner sections with different corner radius to thickness (r/t) ratios

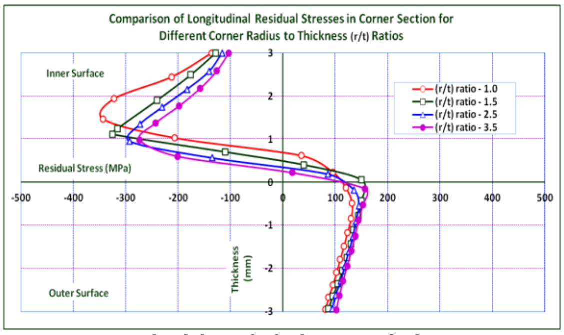

Fig. 11. Longitudinal through-thickness residual stresses in corner sections with different corner radius to thickness (r/t) ratios

It is also observed that the peak residual stress values in inner corner sections with lower (*r/t*) ratios are maximum and tends to drop with the increase in (*r/t*) ratio. The spring back effect is also found to be maximum for the corner sections with lower (*r/t*) ratios and hence the resulting tensile residual stresses in inner corner surface are always maximum for corner sections with lower (*r/t*) ratios. These inner surface tensile residual stresses play a significant role in deciding dynamic fatigue cracking behavior of truck frame rail corner sections, subjected to extreme road operating conditions [13].

In the outer half of corner sections, the peak residual stress values are found to be maximum for the corner sections with higher (*r/t*) ratios and lower for the corner sections with lower (*r/t*) ratios. Also the spring back effect is found to be maximum for the corner sections with higher (*r/t*) ratios. This phenomenon of reducing peak and surface residual stresses in inner corner sections and increasing peak and surface residual stresses in outer corner sections are expected because at a particular point where *r/t* >8, the peak and surface residual stress values at inner and outer half sections becomes equal. Similarly, typical through-thickness equivalent plastic strains predicted from cold forming simulation of frame rail corner sections with (*r/t*) ratio of 1.5 - 3.5 are depicted in Fig. 12.

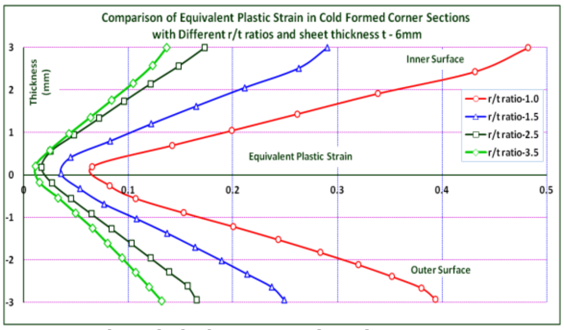

Fig.12. Through-thickness equivalent plastic strains in corner sections with different corner radius to thickness (r/t) ratios

IV. Experimental Measurements

4.1 X-ray Diffraction Measurement

Residual stress measurements were carried out by keeping saw cut press formed frame rail samples on a Rigaku make X-ray diffractometer employing chromium radiation to acquire the diffraction peak at an angle of 156^0 as shown in Fig. 13. $Sin^2\Psi$ technique was used to measure lattice spacing for multiple Ψ angle tilts and the residual stress is calculated from the slope of best fit straight line obtained by least squares regression method. The measurement of through thickness longitudinal and transverse residual stresses on corner and flat web sections was accomplished with the support of spot layer removal method described below.

4.2 Spot Layer Removal Method

X-ray diffraction method is employed for measuring residual stresses on component surface; hence for measuring through-thickness residual stress, removal of material to required depth is needed. Unlike regular layer removal method where rough machining was employed for initial removal of material in entire surface followed by electrolytic polishing [9], in this work a spot layer removal method was adapted for selected area electrolytic etching purpose. In spot layer removal method, the test specimen is completely masked, leaving only a small area of $1cm^2$ getting exposed to electrolyte for layer removal during etching process.

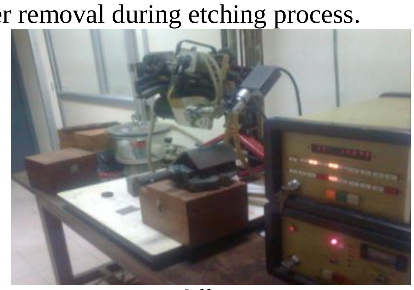
Fig. 13 X-ray diffraction measurement setup
(Courtesy: Central X-ray diffraction lab, IIT Madras, India)

The material removal to required depth is achieved by exposing the surface to a preset time period in 95% brine solution used as electrolyte. As residual stress measurement in a small area at increased depth would be inconvenient for X-ray diffraction measurement, only half thickness residual stresses are measured from outside surface of the section and the remaining half thickness residual stresses are measured from inside surface at the same location.

During electrolytic etching process, enough care was taken to ensure that electrolyte was not heated up and maintained at atmospheric temperature. As the material removal was only though electrolytic etching process, rough machining was completely eliminated and hence there are no machining induced residual stress left in component subsurface. Moreover, in spot layer removal method, the material removal is limited to a small surface area locally thereby it achieves very minimal stress relaxation, Whereas in regular layer removal method, the entire specimen surface is subjected to rough machining followed by electrolytic polishing process.

IV. NUMERICAL VS. EXPERIMENTAL ANALYSIS RESULTS

The comparative numerical vs. experimental analysis of through thickness residual stresses in longitudinal direction of web sections derived from Φ1200 *mm* and Φ1800 *mm* are shown in Fig. 14 and 15 respectively.

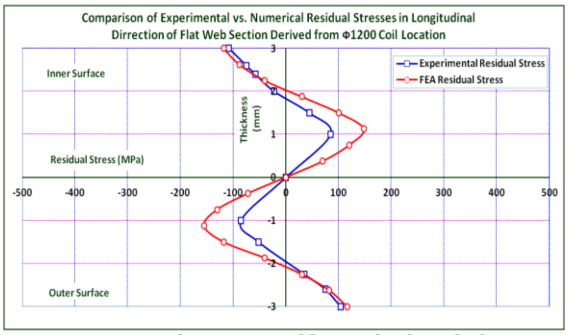

Fig. 14 Experimental vs. numerical longitudinal residual stresses in flat web section derived from Φ1200 *mm* coil location

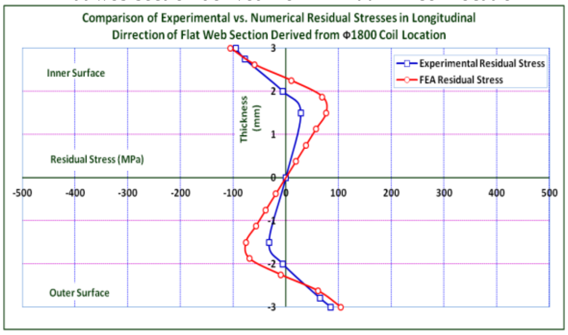

Fig. 15 Experimental vs. numerical longitudinal residual stresses in flat web section derived from Φ1800 *mm* coil location

From the figures, it is observed that the non-linear variation of through-thickness FE residual stresses in coiling direction is closely in agreement with experimental results. Although the experimentally measured residual stresses at depths are observed to be lower than FE predicted residual stresses, the inner and outer surface FE residual stresses are closely matching with experimental results. The drop in experimental residual stresses could be attributed to some amount of stress relaxation during electrolytic polishing process, albeit enough care was taken to minimize the effect. Whereas the magnitudes of coiling-uncoiling residual stresses in transverse direction are found to be very low and hence considered to be insignificant for the comparative analysis.

Similarly, the through thickness residual stress results obtained from numerical simulation of press formed corner sections in transverse as well as longitudinal directions are compared with the experimentally measured residual stress results of formed corner sections with (*r/t*) ratios of 2.5 and 3.5 are shown in Fig. 16 - 19 respectively.

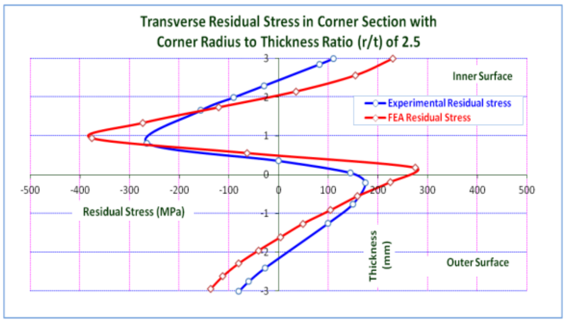

Fig. 16 Experimental vs. numerical transverse residual stresses for corner section with (r/t) ratio - 2.5

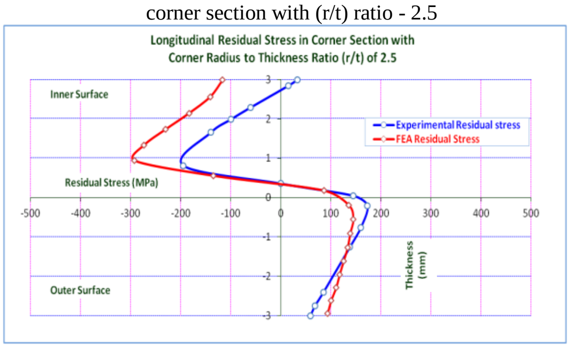

Fig. 17 Experimental vs. numerical longitudinal residual stresses for corner section with (r/t) ratio - 2.5

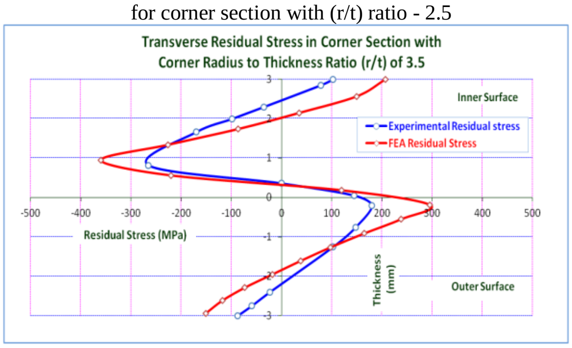

Fig.18. Experimental vs. numerical longitudinal residual stresses for corner section with (r/t) ratio - 3.5

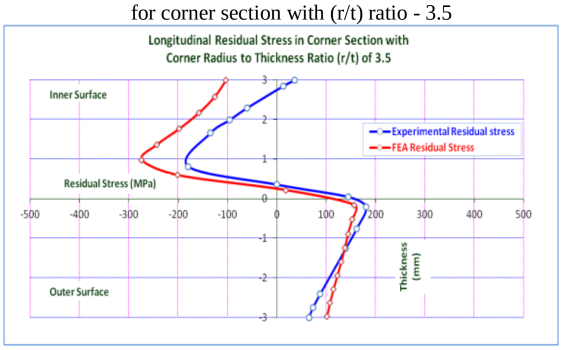

Fig.19. Experimental vs. numerical longitudinal residual stresses for corner section with (r/t) ratio - 3.5

From the figures, it is observed that the non-linear zigzag variation in through-thickness residual stresses from FE simulation is closely in agreement with experimentally measured residual stresses; although the experimentally measured peak transverse residual stresses at depths are slightly lower than finite element predicted peak residual stress results. Again this could be attributed to the stress relaxation due to layer removal during electrolytic polishing process. In both numerical and experimental methods, the maximum compressive residual stresses in transverse and longitudinal directions are observed to be occurring at a location slightly away from neutral axis towards the inner corner surface. The magnitude of maximum compressive stress in inner half thickness is observed to be more than the magnitude of maximum tensile stress in outer half thickness of corner section.

Further, it is observed that the change in direction of residual stresses do not occur on the mid-section, but on the section slightly towards inner corner surface due to the effect of neutral axis shift in bends with small radius of curvature. It is observed that in both numerical and experimental methods, the shift in neutral axis towards inner corner surface is much severe for lower corner radius to thickness ratio sections while comparing with higher corner radius to thickness ratio sections.

VI. SUMMARY AND CONCLUSIONS

In this investigation, coiling-uncoiling and press forming process were numerically simulated with the help of ABAQUS software and the numerically predicted residual stresses were validated with the experimentally measured stress values.

The study results in frame rail web and flange sections revealed that the through-thickness residual stresses follow non-linear distribution with maximum stresses occurring at plastic region away from the elastic core and at the surface.

Similarly, the study results in frame corner section revealed that the longitudinal and transverse residual stresses follow non-linear distribution with maximum stresses occurring at a depth close to neutral axis. Hence it is concluded that the consideration of surface residual stresses alone would not be sufficient for the structural behavior analysis of cold formed frame sections.

From the residual stress distribution, it is worth to note that the mid-section residual stress changes it direction at a section slightly away from mid-section towards inner corner and not exactly at mid-section due to natural shift in neutral axis during press forming process. Also the change in residual stress directions in inner and outer quarter thickness of corner sections is mainly due to elastic spring back effect after forming process.

It is also found that the maximum transverse and longitudinal residual stresses in inner half thickness of corner sections are always higher than the maximum residual stresses observed in outer half thickness of corner sections. The excessive cold working in inner half thickness due to smaller bend radius than the outer half thickness is one of the reasons for this observation. It is observed that the trends and values of experimentally measured residual stresses in forming direction (transverse direction) for different corner radius to thickness ratios (*r/t*) are in agreement with numerically predicted residual stresses.

Whereas in the longitudinal direction (perpendicular to forming direction), while the trends of experimental and numerical residual stresses were observed to follow the same pattern, slight deviations were observed in longitudinal residual stress values and its direction in the inner surface of corner sections.

Apart from the residual stresses, the associated equivalent plastic strains due to coiling-uncoiling and cold forming processes also found to be increasing with decrease in coil diameters and (r/t) ratios respectively. Since these residual stresses along with corresponding equivalent plastic strain values reveal the deformed state of web, flange and corner sections, these parameters in combination with virgin material stress-strain relationships would be useful for defining initial conditions of frame rail sections for further fatigue behavior analysis.

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