Influence of the Residual Welding Phenomena on the Dynamic Properties of a Two-Meter Long Tube with 64 Non-Symmetrical Brackets Welded on a Helical Path

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Abstract

Welded elements of a two meter long tube is considered. The welded structure rotates with 100rad/sec. The non-symmetrical brackets are connected to the tube through by the welds of a curved trajectory that consists of circumferential parts and arbitrary curved part on a shaft surface and disposed on the tube in a helical sequence.

The objective of the study was to explore the axis and hoop stress distribution on the shaft tube and its influence on the dynamic properties of a welded structure. Sample with one element welded to the shaft tube first was studied.

Three approaches were used. Temporal and residual stresses and strains were first obtained by means of moving heat source and by means of solving simplified thermomechanical problem assuming weld laying on being simultaneous along the weld path. Cooling process was important in both methods. Third approach is an own method based on shrinkage forces notion which implementation needs only strength analysis formulation. Its correctness and applicability to the case of weld paths under study was checked.

The residual welding deformations obtained by all methods were then compared with the deformations of samples welded in manufacturing conditions.

Introduction

To simulate welding stresses in a long tube sample with welded brackets the calculation technique that would give appropriate engineering results together with reasonable resource consuming was looked for. Simulation of welding residual phenomena is a developed and developing area with a bunch of methods and approaches. Their applicability to the concrete welded structure is usually studied taking into account a cost of resources. Here the applicability of some of the simulation methods of 2meter tube carrying 30 brackets welded by curved path seams was checked. Incorporated in LS-DYNA® Goldak moving heat source model [1] can be quite time consuming for the big structures and it is art to use it for curved trajectory. The simplified moving heat source model was used instead based on moving thermal flux spot that has correct spot shape and velocity and provides real input welding heat. The flux spot moves discretely (Figure 1), its distribution may be made constant or Gauss [2].

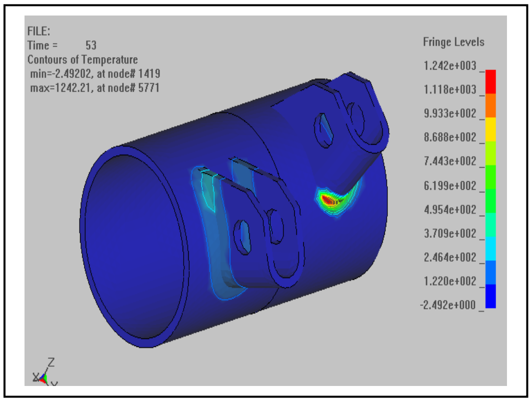


Figure 1 The simplified moving heat source model

Many authors [3,4,5] used inherent strain philosophy proposed by Y.Ueda [6,7] in their research as combined experimental and analytical general approach to determine residual stresses. In.[4] the inherent shrinkage strains for residual stresses calculations induced in numerical analysis by prescribing the initial weld temperature to the weld. The weld cools down and this results in the sample shrinkage. In the [3] it was found that for distortions this method is a good alternative to the moving heat source in predicting residual stresses.

Third used approach of inherent strain incorporation in the final element model for numerical calculation suggests the loading of weld and heat affected zones of the samples with a distributed pressure loads of the value of yield stress of the material for low carbon stainless steel [8,9,10]. Examples described in the paper illustrate the possibilities of the approach in the residual stresses and deformations simulations for the considered welded structure.

The mutual interchangeability of the methods of inducing inherent strain in welded structures is studied. Usage of the simplest ones gives a way to fulfill the inherent stresses incorporation procedure independent from the weld trajectory curvature or welded structure complexity and to fulfill the dynamic analysis taking into account welding prehistory.

While using the approaches with initially heated weld volume(figure 2) the necessity of putting more information in this term must be underlined. For initially heated weld volumes usage in thermal analysis as well as in inherent shrinkage force approach it is crucial to reflect the dependence of geometry from welding regime parameters. Weld zone section profile dimensions and form depend on welding process parameters (welding current, voltage, velocity, heat [11]) as welding pool geometrical parameters are defined by welding process parameters in Goldak [1] moving heat source model.

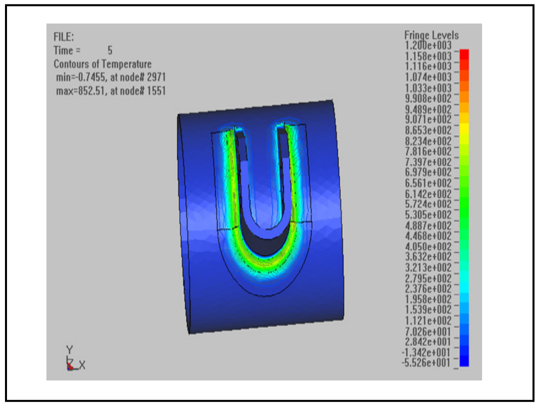


Figure 2 Initially heated weld with weld zone profile calculated in correspondence with welding regimes

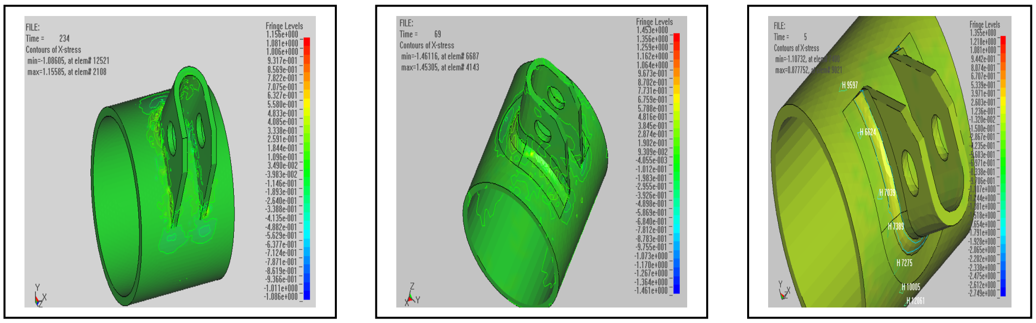
For the weld zone section geometrical parameters there exist dependencies [11] connecting them with welding regimes. They were used to construct a weld zone section. Section were used afterwards for designing the three-dimensional solid and final-element models of weld. It makes possible to study the axis and hoop stress distribution on the shaft tube and its influence on the dynamic properties of a whole welded structure without moving heat source simulation.

The influence of omitting heating stage in welding residual stresses simulation when using initially hot weld that cools down was studied. Therefore four cases were actually analysed. The simulation included both heating and cooling stages. It was carried out in LS-DYNA© 971 MPP Version [12,13,14]. The material models *mat_elastic_plastic_thermal and *mat_ thermal_ isotropic were chosen with material properties dependent on temperature. Used material properties for the room temperature were density $\rho=7.e^{-6}$kg/mm^3, Young modulus= 210 kN/mm^2, yield stress σ_t= 0,4 kN/mm^2,. heat capacity C_p=460J/K, thermal conductivity λ=46W/mK. Puasson ratio ν=0.3, coefficient of thermal expansion β=2.1e^{-6}C^{-1}.

For the dynamic properties of the welded structure dynamic implicit analysis with eigenvalues extracting at arbitrary time moments was used. Changes in eigen frequencies due to residual welding stresses and strains were calculated. Implicit and coupled thermal analysys and implicit structural analysis were carried out. Nonlinear solution method for implicit dynamic analysis and. SMP parallel multi-frontal sparse solver 5 were used to extract 20 first eigen values during the analysis. For thermal methods of residual stresses simulation three types of the results were obtained. Calculations were accomplished for the welded structures not taking into account welding residual phenomena, for the structures with incorporated residual stresses and for the structures with temporary welding stresses during heating stage (modeled with the moving heat flux) and for the cooling stages for all thermal approaches.

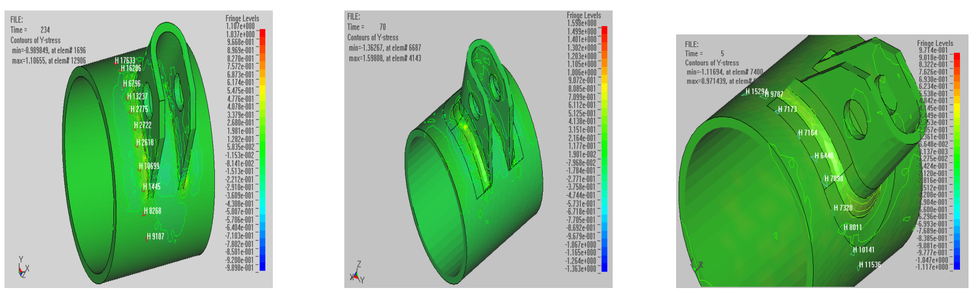
Methods Application to the Studied Object

Comparison of the stresses values and distributions obtained by means of three methods for one-bracket element were made (figure 3,4,6,7).



a) b) c)

Figure 3 - Transverse residual welding x stresses. a)- simulated by moving heat source; b) – simulated by initially heated weld; c) - simulated by shrinkage forces



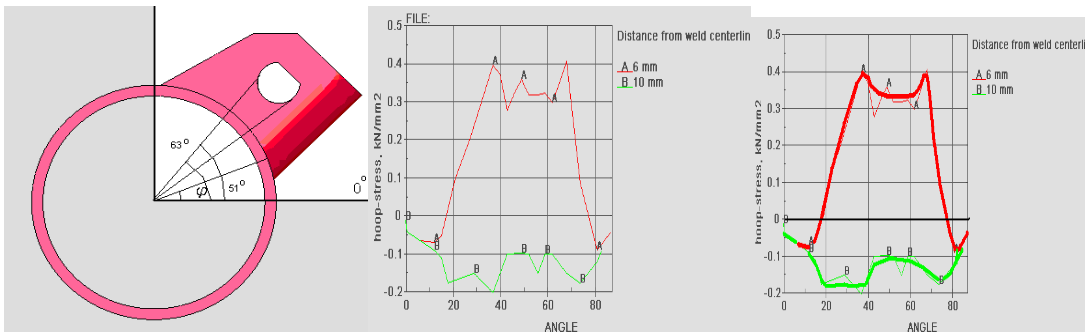
a) b) c)

Figure 4 ‘Longitudinal’ residual welding stresses; a)- simulated by moving heat source; b) – simulated by initially heated weld; c) - simulated by shrinkage forces.

In figures 3,4 contours of transverse x stresses and ‘longitudinal’ y stresses for three simulation techniques are presented. General tendencies in residual hoop and transverse *residual* stresses distributions are preserved in all simulation methods though with different accuracy degree.

All three methods correlate with known residual welding stresses distribution dependencies[11]. Namely, in ‘longitudinal’ direction weld zone material is stretched (plots with σ_{yy} stresses) and heat affected zone areas are compressed. In the direction transverse to the weld weld and weld zones material has maximum of stresses of both signs at the ends of line weld intervals. Dependent on how far from the weld they are measured values of transverse stresses of the middle parts of the weld can be positive, negative or negligibly low (figures 5,6).

Hoop stresses in cylindrical coordinate system calculated from σ_{yy}, σ_{zz} σ_{yz} components of covariant tensor σ are presented here for the moving heat source residual stresses simulation. In figure 5b hoop stresses are given for the 6 and 10mm distance from the weld centerline. Hoop stresses in the weld area are tensile along the bracket length changing its sign from positive to negative at the bracket ends and weld turn to transverse direction. Maximum values of tensile stresses reached the yield stress level (0.4 kN/mm), slight decrease in them occurs for the angles corresponded to in the bracket holes location (figure 5a).



a) b) c)

Figure 5 a) – Range for angle variable changes; b)bracket holes location; c)- hoop stresses 6 and 10mm from weld centerline

The results for residual transverse and hoop stresses are presented by curves each one being for the definite x distance in the X direction from weld centerline. The results are given for the first quadrant of angle variable φ values that localize bracket weld seam (Figure 5a).

Results for the transverse stresses received by moving heat source and initially heated weld simulation are presented below in figures 6 and 7.

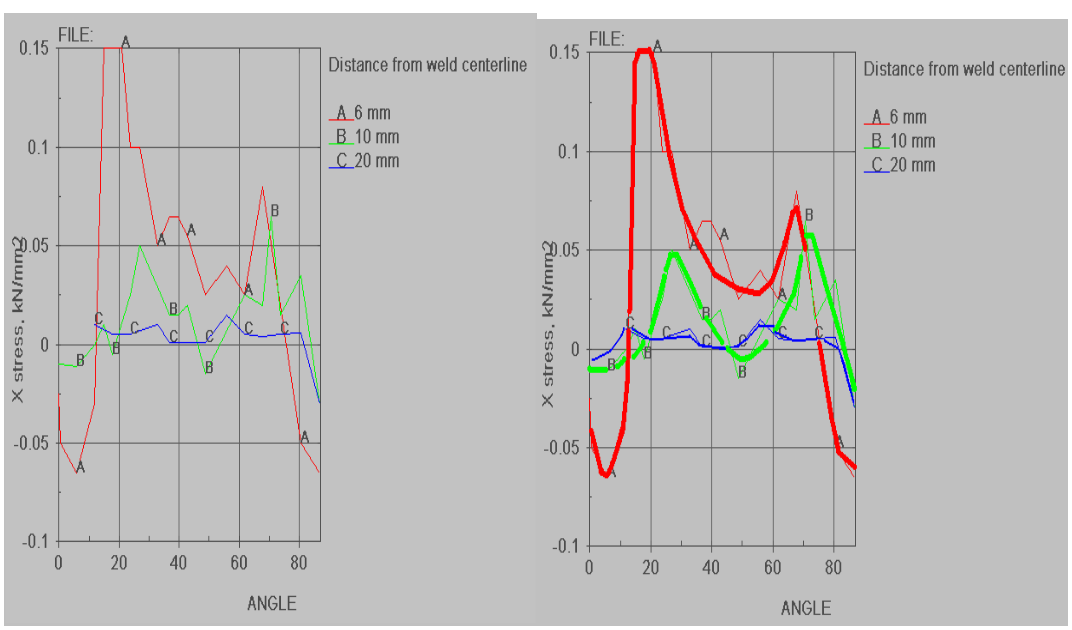


Figure6 - Transverse stresses distribution obtained by moving heat source method

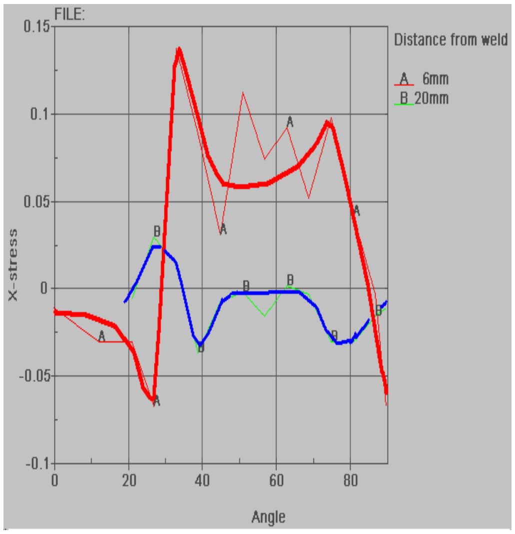
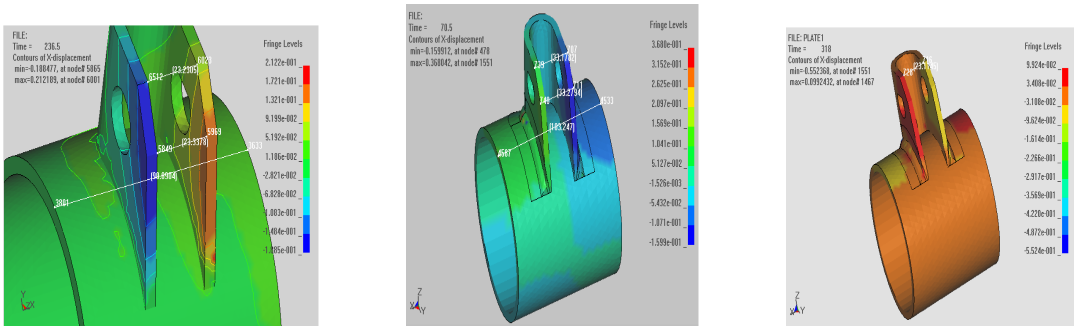


Figure7 Transverse stresses distribution obtained with initially heated weld method.

Results for residual welding deformations

The residual welding deformations obtained by all methods were studied (Figure 8).



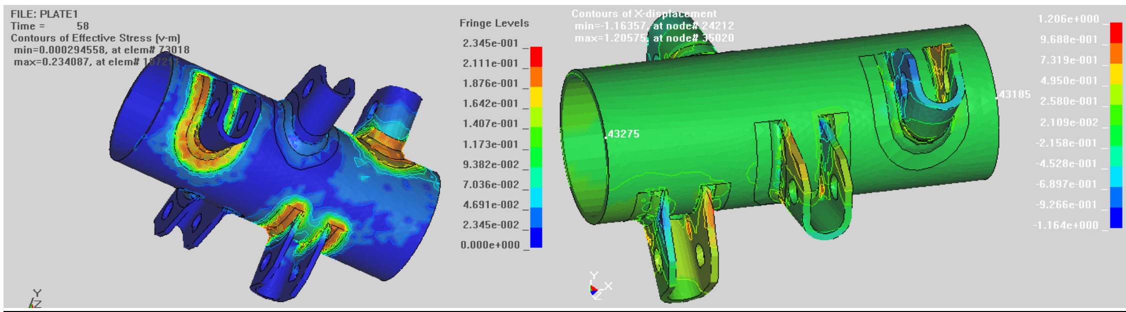
a) b) c)

Figure 8 Measured displacements obtained by different simulation techniques: a) – by moving heat source; b) –by initially heated weld; c) – by inherent shrinkage force method

Table 1 - Residual welding deformations obtained by different residual stress simulation techniques

	calculated by moving heat source method, mm	calculated by initially heated weld method, mm	Calculated by inherent shrinkage force method, mm
Distance 1	0.23	0,338	0,09
Distance 2	0,178	0,279	0,244
Distance 3	0,1145	0,207	0,14

For a great deal of welded structures decreasing of general welding deformations and improving strength and vibration properties could be achieved by rational choice of weld laying out technique. Here the simulation results for a tube with five welded brackets are presented (Figure 4). Table 2 includes the results for three cases: sequentially, from the ends to the center and backing technique starting from the center bracket.



a) b)

Figure 4 - Weld laying on sequence example. a) - residual effective stresses simulation, three welds were already layed on; b) - nodes of final element mesh between which the distance was measured for different weld sequences

Table 2. Residual welding deformations values obtained for different weld sequences

	Sequential weld laying out, mm	Laying out sequence from the end brackets to the center bracket, mm	Backing technique starting from the center bracket, mm
Difference between mesh nodes 43185 и 43275 distance before and after welding	0.8	0.4	0.6

The best technique according to the simulation results is when the welds are laying out from the end brackets to the center one by turns. The change in the measured distances is equal to 0.4 mm. The worst is variant with sequential weld laying out with 0.8 мм residual deformation value.

The obtained difference in final deformations caused by the difference of the weld sequence is about 0.4 mm. During dynamic rotational loads the total amount of residual deformation of studied type may cause parasitic influence on structure misbalance.

As for the worst found sequence the result was quite predictable as many welding reference books [5] suggest that the sequential technique is in most cases the worst one from the point of view of residual deformations. For the rest two sequences only experiment or correct simulation can give an answer, taking into account curvature of a single weld path and complicated special location of all the welds of the welded structure.

Influence of residual stresses and strains on modal properties of the tube

The samples with 1,2,16 elements welded tubes were studied (Figure 10).

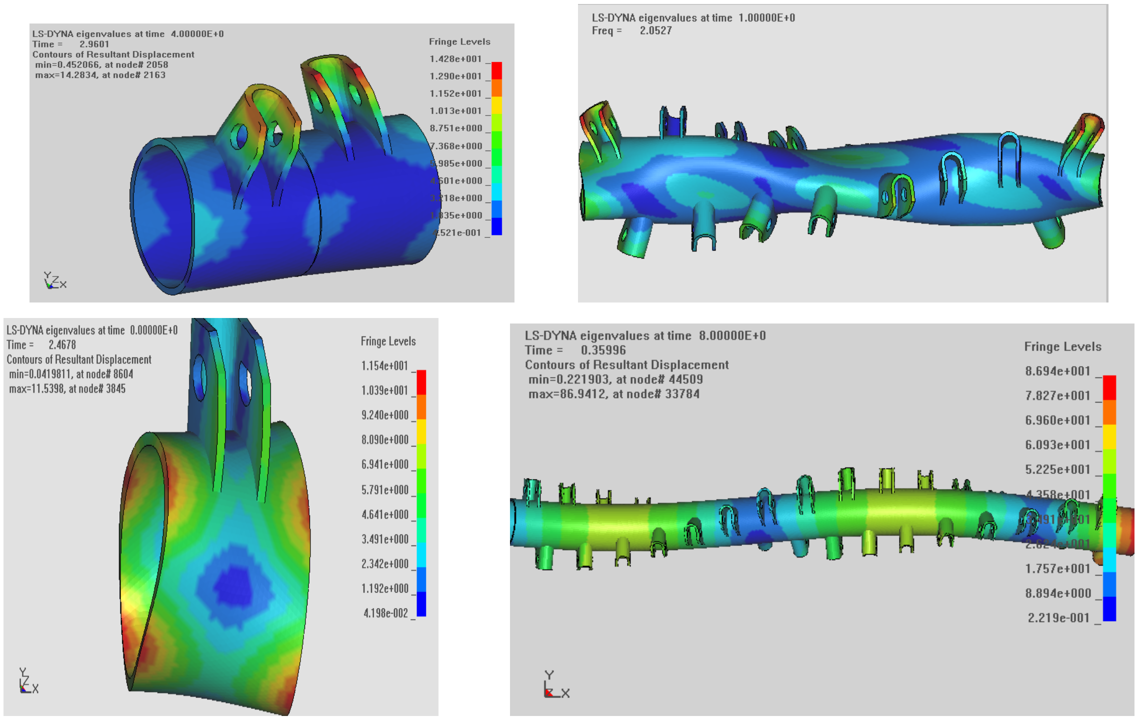


Figure 10 – Eigen mode shapes of 1,2,16,30 elements welded tubes

Comparison of eigen frequencies for a one bracket tube obtained after welding residual stresses simulation by three is given in table 3. Eigen frequencies were extracted after cooling and compared with those received from simulation without incorporated inherited strains.

Table 3 Comparison of eigen frequencies obtained by three simulation methods (kHz)

	Extracted after simulation with moving heat source	Extracted after simulation with initially heated weld	Obtained by shrinkage method
9.284924E+01	9.286271E+01	1.104387E+02	1.052667E+02
1.154406E+02	1.154005E+02	1.408807E+02	1.353538E+02
1.601994E+02	1.600102E+02	1.764150E+02	1.716372E+02
2.404260E+02	2.403280E+02	2.630550E+02	2.519774E+02
6.413889E+02	6.407570E+02	5.863212E+02	5.762998E+02
6.559816E+02	6.558029E+02	6.486449E+02	6.270633E+02
6.611208E+02	6.612809E+02	7.601402E+02	7.333891E+02
9.127382E+02	9.125779E+02	1.095975E+03	1.052710E+03
1.167344E+03	1.167002E+03	1.292210E+03	1.246774E+03
1.368573E+03	1.366354E+03	1.513126E+03	1.459996E+03
1.942169E+03	1.937725E+03	1.928565E+03	1.881478E+03
2.021916E+03	2.022367E+03	2.076611E+03	2.011340E+03
3.013204E+03	3.012352E+03	2.985057E+03	2.876445E+03

The residual welding stresses course changes in the eigen frequencies specter. Changes in values have arbitrary character and the results are much depends on calculation technique. As the moving heat source simulation seems the most natural it can be supposed that the results obtained by this simulation are most credible. Results for the 2,16,30-element tubes before and after heating with moving heat sources are presented in tables 4,5,6.

In table 5 *temporary* and *residual* eigen frequencies are presented for a tube with 16 brackets. The inherent strain is induced by moving heat source. Temporal frequencies are extracted during heating phase. Changes in frequencies due to different weld lay on technique are shown.

Table 4 Eigen frequencies extracted for 2-element tube after simulation with moving heat source (kHz)

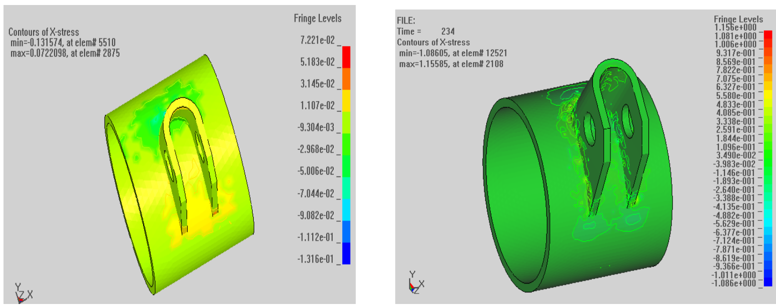
No inherent strains	After moving heat source simulation
	8.660075E+00
	9.212514E+00
1.023306E+02	1.117696E+01
1.145335E+02	1.269594E+02
1.418623E+02	1.379721E+02
1.494249E+02	1.741171E+02
2.980733E+02	1.830374E+02
4.159704E+02	3.459100E+02
5.221508E+02	4.512463E+02
7.031580E+02	4.628426E+02
7.608142E+02	7.471044E+02
7.872755E+02	8.327635E+02
8.059973E+02	8.471193E+02
8.172195E+02	8.796260E+02
8.445934E+02	9.236532E+02
9.878348E+02	9.336906E+02
1.032706E+03	1.023225E+03

Table 5 Eigen frequencies extracted during and after residual welding stresses simulation dependent from different weld lay on technique (kHz)

	Temporary eigen frequencies			Residual eigen frequencies		
No residual stresses	Simultaneously 1	Sequential 20	From center 20	Simultaneously 400	Sequential 400	From center 400
1.833389E+01	**1.773065E+01**	1.793647E+01	1.796857E+01	**1.836205E+01**	1.836626E+01	1.837349E+01
1.937125E+01	**1.801438E+01**	1.833522E+01	1.850251E+01	**1.928441E+01**	1.935987E+01	1.934302E+01
5.896999E+01	**5.654120E+01**	5.714939E+01	5.732276E+01	**5.898581E+01**	5.899888E+01	5.895473E+01
9.441418E+01	**9.012073E+01**	9.121199E+01	9.117220E+01			
9.803586E+01	**9.435680E+01**	9.527775E+01	9.485624E+01	**9.434684E+01**	9.445789E+01	9.467259E+01
1.015594E+02	**9.665133E+01**					
1.020345E+02	**9.773996E+01**	9.809075E+01	9.824594E+01	**9.786201E+01**	9.800620E+01	9.822918E+01
1.108226E+02		9.852190E+01	9.834194E+01	**1.014314E+02**	1.017189E+02	1.014462E+02
1.166159E+02	**1.063095E+02**	1.071232E+02	1.073379E+02	**1.018324E+02**	1.020786E+02	1.018477E+02
1.234364E+02	**1.118607E+02**	1.124464E+02	1.130233E+02	**1.104637E+02**	1.109395E+02	1.107598E+02
1.272537E+02	**1.185051E+02**	1.191084E+02	1.185421E+02	**1.161089E+02**	1.166627E+02	1.167095E+02
1.430310E+02	**1.216767E+02**	1.223021E+02	1.221925E+02	**1.229787E+02**	1.231732E+02	1.237674E+02
1.499146E+02				**1.268308E+02**	1.271372E+02	1.275611E+02
1.663373E+02	**1.373126E+02**	1.379072E+02	1.379310E+02	**1.425323E+02**	1.430040E+02	1.431902E+02
1.833389E+01		1.433707E+02	1.443874E+02	**1.490338E+02**	1.498574E+02	1.500638E+02
1.937125E+01	**1.578569E+02**	1.595747E+02	1.600857E+02	**1.657616E+02**	1.663192E+02	1.663457E+02

Stress values due to rotation compared to welding residual and resultant stresses

Stresses from dynamic rotation loads and residual welding stresses differ in values and distribution but concentrated in weld and weld affected zones of the brackets. For the most remote bracket unit of a tube rotating at angular velocity 1000rot/min resultant stresses were obtained. They were compared with stresses that would be observed during rotation if the residual welding stresses were not taken into account (figure 11a) and pure residual welding stresses (figure 11b)



a) b)

Figure 11 Transverse stresses a) -from pure dynamic rotation loads; b) -residual welding stresses

Results for transverse stresses values at 6 and 10 mm distance from weld centerline are given in table 5.

Table 5 Transverse stresses (kN/mm^2)

φ	0	5	10	15	20	25	30	35
Rotational, 6mm	-.017	-.013	-.015	0.021		-.0105	0.001	
residual, 6mm	-0.1	-0.13	-0.08	-0.04		0.035	0.165	0.02
resultant, 6mm	-0.09	-0.06	-0.05	-0.06		-0.01	0.11	-.025
Rotational, 10mm		0.001	0.004	0.003	0.004	0.013	0.001	0
residual, 10mm	-.064	0.02	0.015	-.001	0.15	-0.01	-0.05	-.025
resultant, 10mm	-0.03	0.02	0.03	-.01	0.12	0.16	-0.05	-0.02

Table 5 Transverse stresses (kN/mm^2) (cont'd)

φ	40	45	50	55	60	65	70	75	85
Rotational, 6mm	-.005	-0.005	-.003	-0.003	-.001	0.003	0.0075	0.0165	0.01
residual, 6mm	0.175	0.175	0.16	0.32	0.4	0.25	0.25	0.16	-.002
resultant, 6mm	0.1	0.17	0,14	0,3	0,38	0,215	0,235	0,2	0.001
Rotational, 10mm	-.001	-.0025	-.005	0.0075	-0.12	- 0.011	-0.011	-0.016	
residual, 10mm	0.02	0.09	0.04	0.15	0.1	0	-0.08	-0/08	
resultant, 10mm	0.05	0.06	0	0.12	0.05	-0.02	-0.05	-0.08	

In the heat affected zones residual transverse stresses one order bigger then dynamic stresses. At the weld root (6mm distance) resultant stresses being lower then residual. Thus for 1000 rot/min residual stresses are first to be taken into account while considering strength properties of a rotating tube. Positive aspect is that residual welding and dynamic stresses are counter act at the weld zone border.

Conclusion

Investigation of the residual welding phenomena influence on the general dynamic properties of welded tube structure was made. Described examples illustrate the possibilities of residual strain incorporation in a model for further dynamic numerical analysis. Different ways of that incorporation are studied on a one bracket tube element. Result transverse and hoop stresses values and distributions were checked for correlation with known results. Methods based on the initially heated weld final element model incorporation in FE environment can be used for welding residual stresses simulation independent from weld trajectory curvature or welded structure complexity. Preliminary information about welding conditions is included into the 3d solid model of weld and heat affected zone. Inherent strain incorporating techniques are used for prediction of the residual welding stresses of a 2m long tube and its resultant stresses during rotation. Welded structure prehistory is taken into account for tube eigen values calculation.

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