Large-scale distortion analysis of the welding and thermal straightening process chain

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Abstract: *An coupled analytic-numerical model for calculation of distortions arising by welding fabrication is introduced. Target of the analytical model is the calculation of the inherent strains after the local thermal-mechanical influence of the welding or thermal straightening process. Following the fabrication processing chart the strains are loaded on an elastic FE-model of the structure and the residual stresses and distortions of the whole structure are calculated. The consideration of welding and thermal straightening scenarios, inclusively the assembling stages, is done by taking into consideration the intermediate variation of the strain state in the FE-model of the structure at every processing step. The important physical relations are demonstrated. The model is intended to be used for solving industrial tasks, i.e. intending acceptable precision and calculation time as well as low simulation costs.*

Keywords: COMPUTATIONAL WELDING MECHANICS, WELDING DISTORTIONS, THERMAL STRAIGHTENING, INHERENT STRAIN, FE-SIMULATION,

1. Introduction

The welding distortions are still one of the main problems in welding technology. It decreases the quality of the welded structure, complicate the smoothly accomplishment of the manufacturing process and increase the cost of post treatments. Since several decades, thermal straightening is an established technique for improving welding structures, figure 1. By the thermal straightening additional deformations are set into the structure, which lead to decreasing the out-of-plane distortion and increasing the in-plane shrinkage. Prediction and control of the welding distortions and the effect of the thermal straightening process, during the early stages of a designing cycle, allows avoiding expensive engineering correction that could occur later.

Fig. 1 *Railway carriage after thermal straightening, ©ALSTOM Transport Deutschland GmbH, Salzgitter[1].*

In the praxis, the straightening process guidance and parameters are chosen on the background of practical experience, complemented with additional time- and cost-intensive experiments. Unfortunately, it is impossible to capture the influence of the different structural stiffness, materials and residual stresses state after welding with this approach.

Another approach seems to be a welding - thermal straightening distortion simulation, based on the computational welding mechanics. Particularly in welding, analytical [1-8] or numerical [9-15] models achieve a solution to the problem. The application of analytical models is strongly limited due to the necessary simplifications of the physical phenomena. However, the numerical models are free from such limitations. They cover a large number of topics; one of which is the prediction of the residual distortions caused by the mutual influence of highly localized heat input, the material behavior, the initial inhomogeneous temperature and stress-strain states and the response of the whole structure as well.

Despite the benefits the numerical models, one great difficulty of their industrial utilization is the complexity of the problem formulation and necessity of number of input data that, in many cases, are not available. In addition, the conventional numerical thermal-mechanical welding simulations, combined with straightening simulations are not feasible, as they require significant computation costs and highly qualified personnel. These difficulties rise when the subject of the simulation is a large, complex welded structure, which often makes the employment of numerical methods in the praxis inefficient. Hence, there is a great demand for simple welding simulation models and approaches, which allow for quick distortions prediction. The technical literature gives among the works [5-9] a set of validated applications that are limited to simple welded joints [14-17].

To answer this need, an innovative solution approach for simulation of welding distortions has been developed in earlier works [16,18]. The approach is an integration of analytical and numerical calculation’s procedures in a hybrid model. The analytical procedure calculates the shrinkage volume and strains distribution in it, representing the weld seams, based on the theoretical works of Okerblom [2], Gatovskij [4] and Vinokurov [5] implemented in a novel enhanced model [18]. The calculated strains are than applied to the global FE model in order to predict the distortions of the structure during the welding stages, as well as their residual state [18].

The aim of this article is to demonstrate the analytical models for calculation of inherent strain by welding and thermal straightening processes as well as their implementation it into the welding simulation procedure. Thus, to suggest an engineering tool that reduces the development time, costs and increases the efficiency of manufacturing.

2. Concept of the coupled analytical-numerical model

By welding, the analytical approach calculates the shrinkage volume, representing the weld seams, based on the theoretical works [3-7]. The introduction of complex semi-empirical relations allows to take into consideration the relevant factors and to reach the need adequacy. The calculated plastic strains are then loaded (as inherent strain) on the global FE model in order to calculate the distortions of the structure during the welding (after every one weld), as well as the global stress field. For this purpose, an elastic FE-analysis, which is fast and needs a simple material data definition, is carried out. The stress state in the structure, obtained from the numerical calculation, returns to the analytical one, using a loop statement for every next weld. This procedure allows taking into consideration the influence of the welding sequence as well as the changes of the clamping conditions and variation of the structure restrain.

The solution of the deformations problem, in the thermal straightening, bases on the hypothesis for prolonged accumulation of plastic strains, caused by the irregular thermal-deformational field around the heat source, the restrain intensity and the variation of the stress state as well. This govern the basic approach for solving such problem (figure 2), in which a thermal-deformation calculation is carried out, taking into account the nonlinear material behaviour, as well as the field of initial elastic strains. The last one could be due to residual stresses, caused either after welding or already completed straightening works as well. That means the simulation of straightening follows the simulation of welding and consists of sequential calculations of plastic, i.e. inherent, strain of every one heat spot.

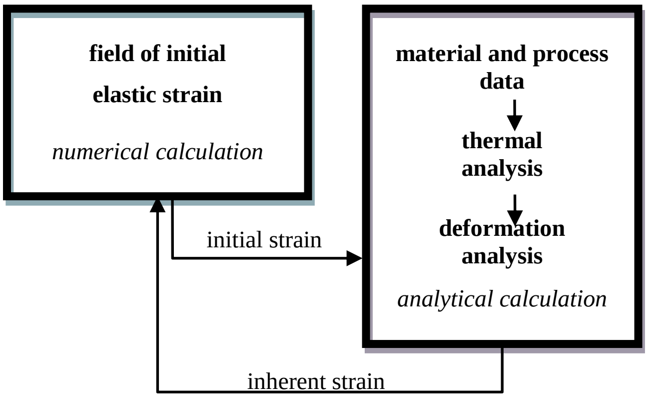


Fig. 2 *Coupled analytical-numerical analysis*

On this place is not wroth to underline that the both, welding and thermal straightening simulations may be executed in an arbitrary sequence, following various manufacturing charts of the fabrication plan.

3. Analytical model

3.1 Welding

Purpose of the analytical model (also shrinkage model) is determination of the area where plastic strain appears. As mentioned above, scientific background of the model for welding build the plastic strains evolution under temperature dependent ideal elastic-plastic material behavior [3,5-7]. In case of long welds, the mechanical problem can be considered as uniform stress-strain in the weld cross section with known distribution of the maximal temperatures. The thermal strain (expansion and shrinkage) in the longitudinal direction is constraint by the surrounding cold metal, which realizes infinity restrain. After this model the zone with the plastic strains w_{pz} is defined by certain maximal temperatures, i.e. by the maximal thermal strain $\alpha(\Delta T_{max})$ equal to yield strain ε_Y pus initial strain ε_0 and $2\varepsilon_Y$., figure 3.

For the longitudinal component of the inherent strain, it is govern by the equation:

$$\varepsilon_x^* w_{pz} s = \int_0^s \int_0^\infty \varepsilon_x^{pl} dydz = s \int_{\varepsilon_Y+\varepsilon_0}^{2\varepsilon_Y} y\left(\varepsilon_{\max}^{th}\right) d\varepsilon_{\max}^{th} ,$$

and for the transverse component, respectively:

$$\varepsilon_y^* = \frac{1}{w_{pz} s} \int_0^s \int_0^\infty \varepsilon_y^{pl} dydz \cdot$$

Herby the ε^* is the inherent strain to the corresponding component direction (x or y), s is the thickness of the sheets, w_{pz} is the width of the plastic deformed zone, ε_Y is the strain at the yield stress, ε_0 is the initial strain (that is elastic in nature), ε^{pl} are the plastic strain components (x or y), $\varepsilon_{\max}^{th}$ is the thermal strain at the maximal temperature.

Different influences on plastic strains, for example relation of the heat input to the thickness, external and internal stiffness, strain hardening, existing plastic strains in the weld, solid state transformations, clamping conditions or multi-run welding can be considered by semi-empirical correction functions [6,17]. Capturing all these effects on the arising distortions simultaneously is not possible as they also affect each other. In the technical literature is among the works [5-9] a set of applications published and compared with experimental results for simple welded joints [14-17] or large [16,18].

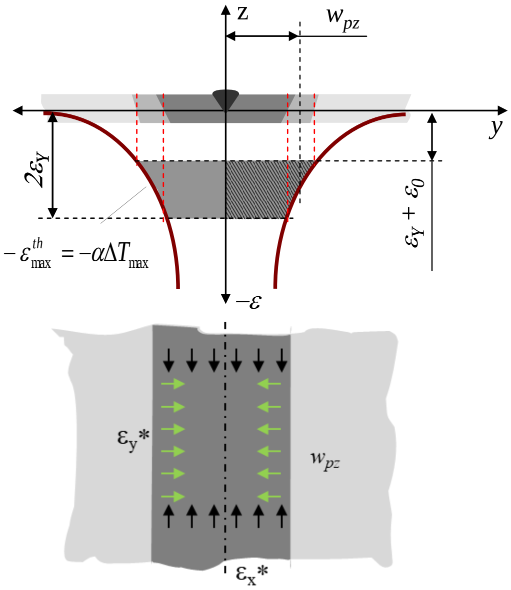


Fig. 3 *Formation of plastic strain by welding*

The distribution of maximal temperatures can be obtained by derivation of the quasi-stationary temperature field. In that order, diverse analytical solution can be used. The current model for welding, for example, uses a combination of moving point heat source in semi-infinity body and moving line heat source in thin plate [18,19]. The combination factor depends on the welding process, heat input and the thickness of the sheets.

3.2 Heat spot

If the heat source is fixed, as it by thermal straightening with heat spot is, the kinetics of plastic strain evolution vary. Assuming a large circular disk, subject of heating at its center and followed by cooling, an axial symmetric mechanical problem should be considered, figure 4.

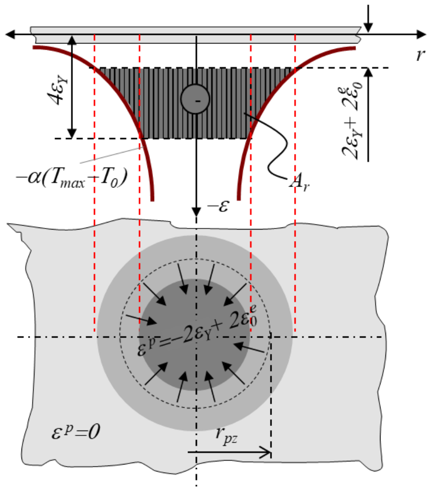


Fig. 4 *Radial distribution of the plastic strains after heat spot.*

In this case, the surrounding cold metal behaves elastically during both heating and cooling, and the strain occurring in it is equal to the elastic strain in the heated core. Hence, in a stress free disc the plastic strains arise in domain between maximal thermal strain $\alpha(\Delta T_{max})$ equal to yield strain $2\varepsilon_Y+2\varepsilon_0$ and $4\varepsilon_Y$ respectively, see plastic deformed zone r_{pz} on figure 4. Presence of any initial strain will shift the thermal strain curves with its value and sign, like to heat line problem [21,22]. Thus, the shrinkage volume (v_r in mm^2 mm/mm) in case of heat spot is given by the equation:

$$v_r = \int_{(2\varepsilon_Y+2\varepsilon_0)}^{4\varepsilon_Y} A_r d\varepsilon^{th}$$

where A_r is the area bordered by the maximal thermal strain and integral limits $2\varepsilon_Y+2\varepsilon_0$ and $4\varepsilon_Y$ respectively. Hence, the radius of plastic deformed zone is:

$$r_{pz} = \sqrt{\frac{v_r}{\pi\left(2\varepsilon_Y+2\varepsilon_0\right)}}$$

To apply the model in the overall calculation procedure an appropriate solution of the thermal problem is need. In the common case, the solutions with instantaneous line heat source [19-23], enhanced to non-uniform initial temperature T_0, suggested by [24] give satisfactory results.

3. Application of the analytical-numerical model

To demonstrate the capability of the coupled analytical-numerical model a welding simulation, followed by simulation of a thermal straightening is carried out. The subject is a qualitative demonstration, i.e. plausibility proof of the model. To do it, a complex structure with 8 welds was chosen [20], figure 4. It is made from two T-profiles being joined with the plate by weld 1 and 2, two L-profiles joined with the plate by weld 3 and 4 and with the T-profiles by the welds 5, 6, 7 and 8. Each wall thickness is 3 mm. The distance between T-profiles is 800 mm. The material is a mild structural steel. For the purpose of simulation, reference welding process and parameters are chosen.

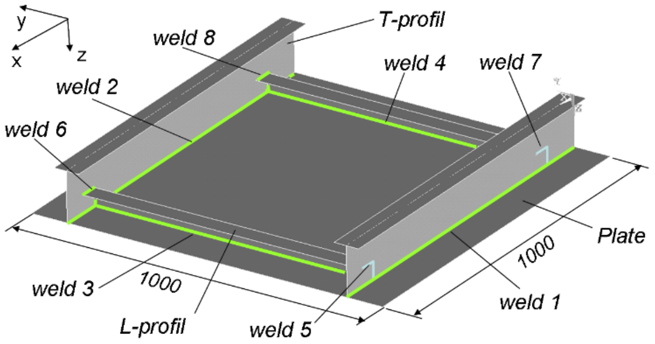


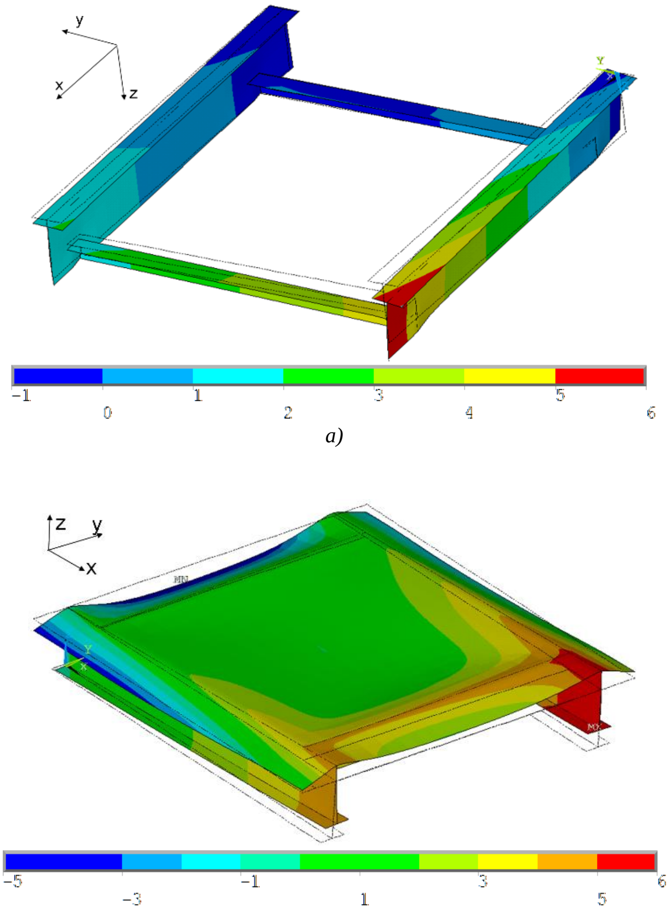
Fig. 5 *Model of the complex structure with dimensions and welds (upside down)*

Object of the analysis are the distortions in the sheet, closed by the frame. The blades are not considered by the analysis. According to [20] great angular distortions should be expected if at the beginning the L-profile and the T-profile are welded together (welds 5 – 8), afterwards they are joined to the sheet by welds 1 and 2 simultaneously and finally by 3 and 4.

For the distortion calculation using the hybrid model a finite element model with shell elements was generated. For the purpose of simulation, the mesh is very coarse and just refined in the supposed areas of plastic deformation, where the structure is loaded. Thus, in those domains the element size is about 20 mm (according to the analytical solution). For the reason of free forming, only the node in the middle of the plate (x=500, y=500) has fixed DOF (translation and rotation). The loading is realized by longitudinal and transverse strains, linear distributed along the thickness, in three steps according to the welding scenario.

The strains in the longitudinal and transversal directions, as well as their centroid are calculated by means of the analytical model, stated above, under stress free condition. At this stage, a reference temperature distribution is applied. For the third step, the residual stresses after the second step (tension in the plate and compression in L-profile along welds 3 and 4) are taken into consideration. The obtained results are presented exemplary by the field of displacement in Z-direction (out-of-plane), figure 6.

The distortions, obtained by the coupled analytical-numerical model satisfy qualitatively the expected [20]. The average values of calculated bending and transverse shrinkage in the plate, between the T-profiles, in the middle of the structure, after welding are as follow: ΔZ = 3 mm and ΔY = 0,2 mm.



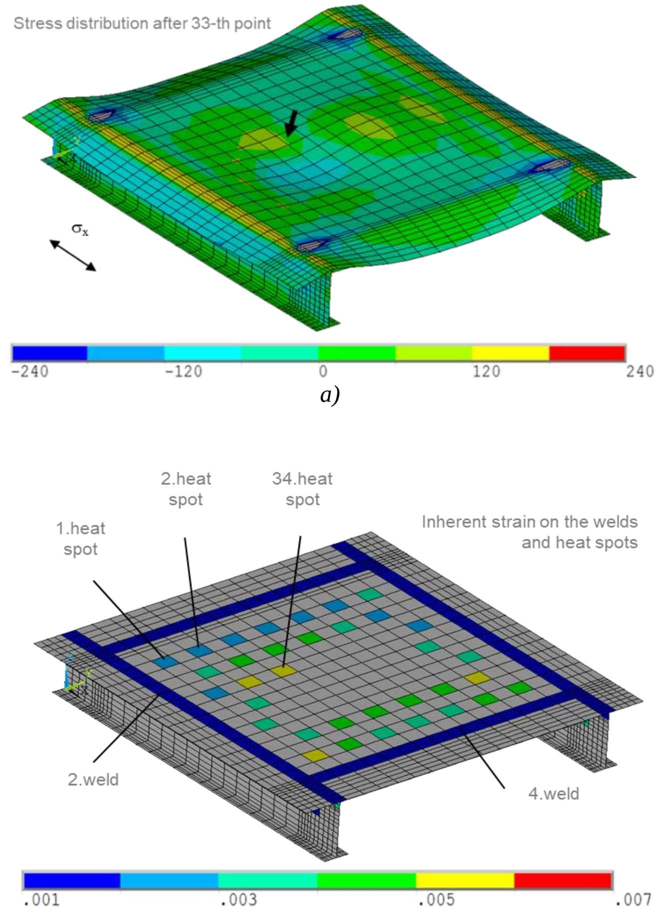
a)

b)

Fig. 6 *Bending of the structure (displacement in z-direction, mm), scaling x75: (a) after welding the profiles, (b) after welding entire structure*

Based on the calculated welding distortions a thermal straightening simulation is carried out. It is done by means of 46 heat spots, with distance about 100 mm each other. The process parameters are also reference, so that the nominal width of plastic zone corresponds to about 20 mm. The heating sequence follows a spiral trajectory, from outside to the middle, in 46 load steps, figure 7.

The inherent strains for every next spot and direction are recalculated, taking into consideration the actual strain (or stress) vector from the current element. Hence, it varies from spot to spot in the range between several times and zero. At this stage the recalculation was done according to the relation from [18,24]. The calculation time for the entire simulation, welding and straightening, took 5 – 10°min. The obtained results, after the last spot, confirm the expected result – straightening the sheet (figure 8) and accumulating additional shrinkage in the plane. The calculation shows a reduction of the bending line to less than 1 mm, figure 9 (a). The in-plane shrinkage of the structure (exemplar distance between the T-profiles), rise from 0,2 mm to 0,25 mm (figure 9 (b), blue curve).



a)

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Fig. 7 *Loading of the 34 heat spot: a) stress field (in MPa) after 33. heat spot, b) inherent strain, loaded to the elements at 34. heat spot*

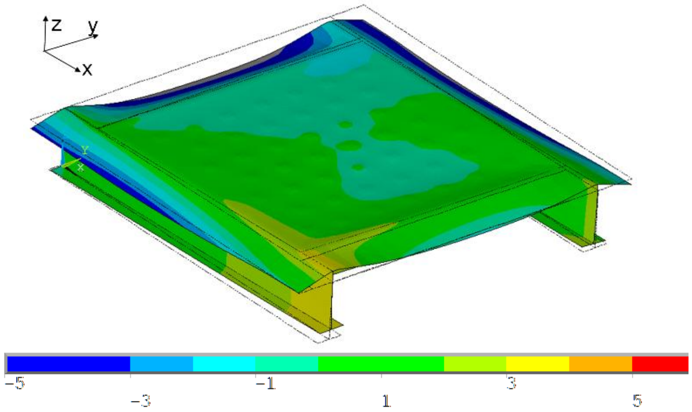
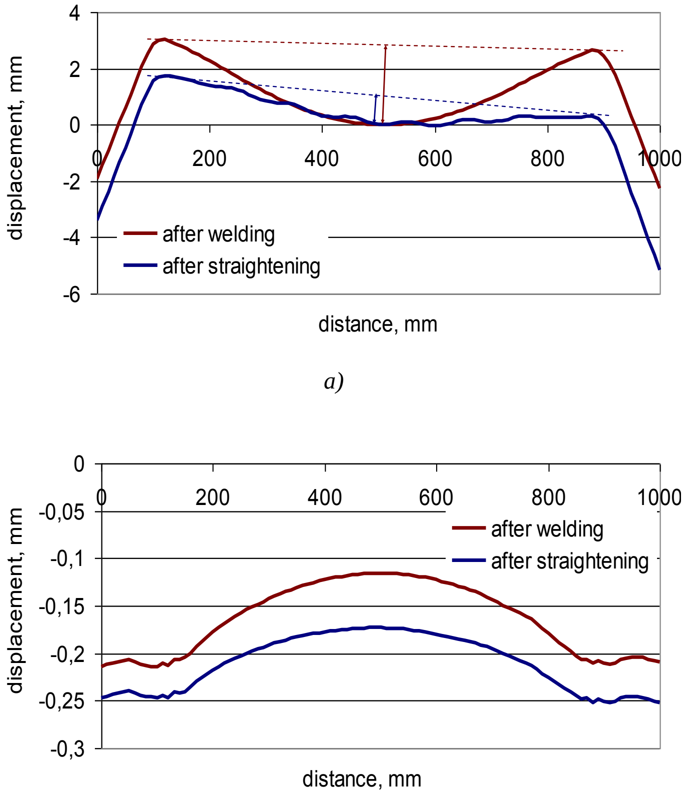


Fig. 8 *Bending of the structure after straightening (displacement in z-direction, mm), scaling x75*

The examination of intermediate steps shows that not all heat spots are reasonable, i.e. some of them don't affect the distortions or cause a negative effect. For example, the angular distortions after heat spot 41 are equal to the final and after 44 spot they reach the minimum. Never less, it is an evidence that the model provides possibilities to determine the structural shrinkage as well as to analyze or optimize the straightening procedure.



a)

b)

Fig. 9 *Comparison between "after welding" and "after straightening": (a) out-of-plane displacement, (b) transverse shrinkage*

4. Conclusions

To find the optimal process guiding and parameters for a thermal straightening of welded structures as well as the resulting shrinkage, the procedure of time- and cost-intensive experiments is still commonly used. For this purpose, the employment of the contemporary thermal-mechanical finite-element-simulation is increasing. However, in range of large structures with multiple weld seams, the complete thermal-mechanical FE-simulation is not rational.

The limitations of the common thermal-mechanical FE-simulation, regarding the distortions calculation of large welded structures are summarized. An abstract about the existing simplified approaches as well as their inadequateness is given. Based on the need for fast and adequate precise approaches for calculating welding distortions in large structures a novel and practically relevant model is suggested and demonstrated.

To demonstrate model capability an analysis of welding distortions, after welding and subsequent thermal straightening, in a large structure has been carried out. Furthermore, the qualitative interaction of the thermal straightening and the welding processes is analyzed for one reference scenario. For this purpose, the variation of the stress state in the structure, during welding and straightening is taken into consideration. The results of the analytic-numerical hybrid model match the expertise and the expectations.

The example is performed using ANSYS$^{®}$ FE-code. The calculation time was about several minutes, on a common PC. The coupled analytic-numerical model shows enormous potential regarding to the reduction of the computation time, as well as significant reduction of the pre-processing time. However, there is a demand for future research and development activities over finding the proper equation for the maximal temperature distribution, considering the most used flame and induction heat sources, as well as cooling conditions due to fixing tools. In addition, the process parameters, derivation of the material parameters for different structural materials as well as different numerical model parameters should be characterised.

Abbreviations

DOF	degree of freedom
IP	integration points
A_r	is the area bordered by the maximal thermal strain and integral limits $2\varepsilon_Y+2\varepsilon_0$ and $4\varepsilon_Y$ respectively
b_{pz}	width of the plastic deformed zone
r_{pz}	radius of the plastic deformed zone
v	shrinkage volume
ΔY	overall in-plane shrinkage in Y-direction
ΔZ	maximal out-of plane displacement
ΔT_{max}	maximal temperature increment
T_0	initial temperature
α	thermal expansion coefficient
ε_Y	strain by yield limit
ε_0	initial elastic strain (residual strain from preliminary load steps
ε^*	inherent strain
ε^{el}	elastic strain
ε^{pl}	plastic strain
ε^{th}	thermal strain

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