Update of a Linear Regression Model to Predict Forming Limit Curves from Tensile Test Data

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1 Abstract

Forming limit curves (FLCs) are widely used for the feasibility analysis of deep drawn steel components and the final tool design. The experimental determination of the FLC is usually based on Nakajima tests, which are evaluated according to the ISO 12004-2 standard with the intersection line method. In recent years the additional determination with the time dependent method [1] is used since it more accurately describes the increased forming potential of modern high ductility steel grades found in practical experiments.

The experimental determination of the FLC is time consuming and expensive. Therefore, models are used to predict the FLC, based on simple and frequently available tensile tests results. They enable the easy and quick identification of the forming potential of newly developed steel grades. These models can also be used to analyze the influence of sheet thickness and material properties on the FLC. The implementation of the Abspoel model [2] in different finite element (FE) solvers shows the practical demand.

voestalpine developed a linear regression model which predicts the minor and major strain for each FLC sample geometry, published in 2012 [3]. This model was based on 332 FLCs, determined by the intersection line method for the steel grades available at that time. Now, ten years later, the useable database increased to 771 FLCs determined by the intersections line method and 254 FLCs determined by the time dependent method. The database includes novel steel grades, such as high ductility and martensitic steels, and steels with tensile strengths up to approx. 1400 MPa. It also contains FLCs of innovative, high strength, hot rolled steel grades.

In this paper the process of data selection and model development is shown. Different subsets of parameters from available material test data, like sheet thickness *Th*, yield stress R_{p02}, tensile strength R_m, uniform elongation A_g and fracture strain A_{80} are used as independent predictor variables.

To get an accurate assessment of the models potential and limitations, the model FLCs are compared with a comprehensive set of experimental FLCs. Those experimental FLCs are freely distributed by voestalpine in form of LS-Dyna material cards. The evaluation shows, the capability of this updated model to accurately describe experimental FLCs, based only on tensile test data.

2 Introduction

As a sheet steel producer, numerous FLCs must be obtained by conducting Nakajima tests. They are necessary to describe the forming potential of newly developed steel grades, to define the influence of individual steel coil properties on their formability, for the approval process with customers and in general as a part of customer service. These tests are not only expensive, but they are also time consuming and therefore the necessary results can come too late for their intended application.

Therefore FLC models were developed, which describe the FLC based only on tensile test results, like Keeler [4], Abspoel et al. [2], and Gerlach et al. [5]. The advantage is, that tensile test results are much more inexpensive than Nakajima tests and are often included in test certificates or the quality control process.

With Schmid et al. [3], published in 2012, we also presented a simple to use FLC model. This model describes the major and minor strain for each relevant FLC sample geometry. The input parameters are thickness *Th*, fracture strain A_{80} and material class (mild or high strength steel grades).

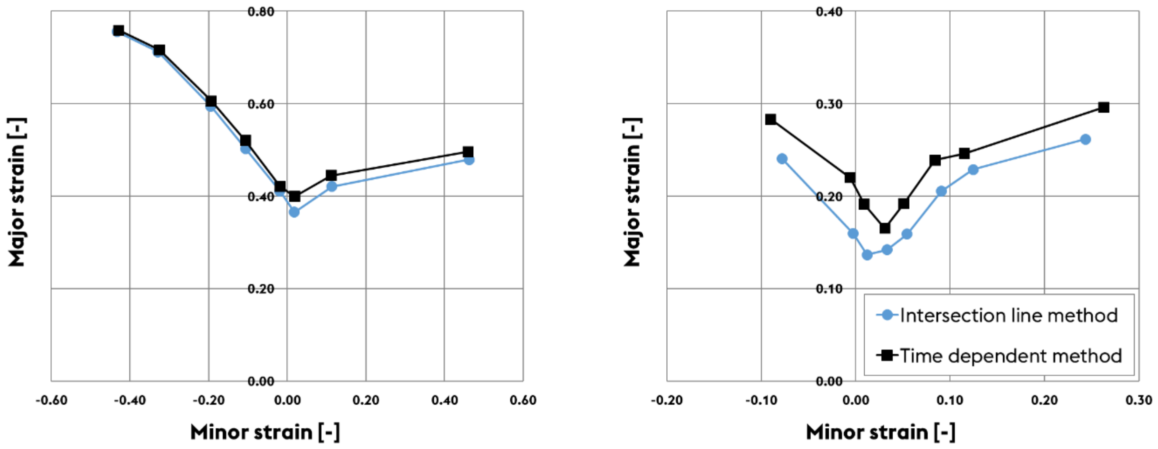

Figure 1: Examples for the difference between experimental FLCs, depending on the chosen evaluation method – intersection line and time dependent method, (left) CR3 0.70 mm and (right) CR590Y980T-DP 1.52 mm.

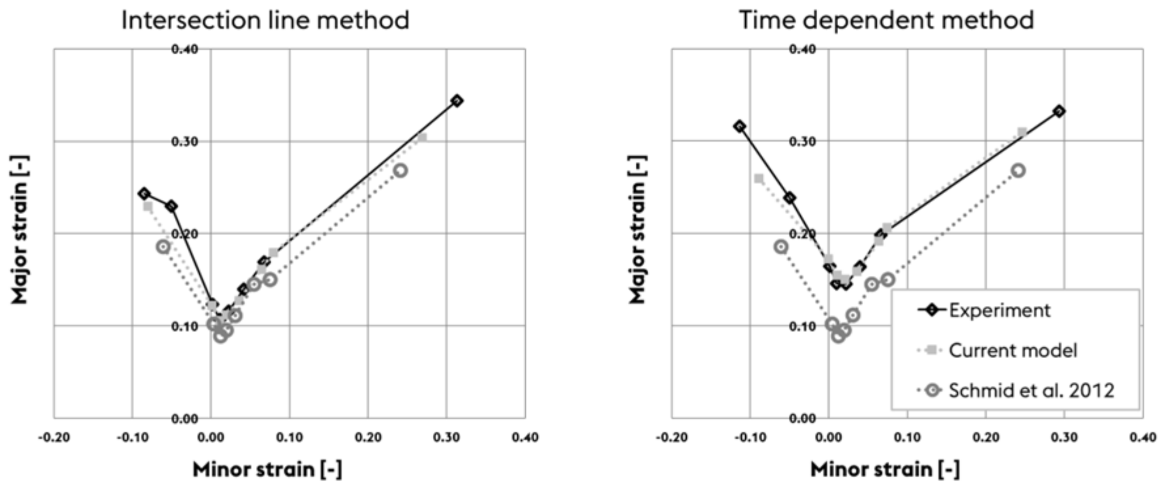

Figure 2: FLC of a CR780Y980T-CH GI with 1.22 mm thickness, determined by the intersection line method (left) and the time dependent method (right). The model prediction of the previous model and the current model is shown as an example.

The model of 2012 was based on 332 FLCs. Since then, the number of available FLCs more than doubled, but also the quality of the available database changed significantly in the last ten years, mainly due to the following reasons.

- New high strength steels with tensile strengths R_m of 1000 MPa and above were developed. Those are classic dual phase and complex phase steels, 3rd generation steels with improved formability, and martensitic steels which closed the strength gap to the press hardened steels. Work was also carried out successfully in the further development of mild steels, high strength low alloy steels, and hot rolled steel grades.
- The FLC evaluation according to the ISO 12004-2 standard with the intersection line method was expanded by the time dependent method [1], which is now available in commercial software tools. The latter method results in higher FLCs, as shown in Figure 1, which more accurately describe the experimentally observed increased forming potential of modern high ductility steel grades. This effect is stronger for advanced high strength steels, like the CR590Y980T-DP, than for mild steels, like the CR3.

While the model from 2012 was able to describe the FLCs quite accurately at the time, Figure 2 shows the two current shortcomings of the Schmid et al. 2012 model exemplarily. It underestimates the intersection line method FLC of a modern CR780Y980T-CH, and it is not able to take the effect of the time dependent method into account, while the current model is able to do both.
To obtain the current model, we applied the proven linear regression approach with the current FLC database. This database consisted of 771 intersection line method FLCs and 254 time dependent method FLCs, linked to the associated tensile test data.

3 Model development

The linear regression model of Schmid et al. 2012 [3] was slightly adapted during the development process. Eventually we used the following basic approach.

3.1 Linear regression model

A standard linear regression model for predicting FLC minor and major strain is used. Data values Y_i of dependent (or target or output) variables are realisations of *n* random variables,

$$Y_i = b_0 + b_1 x_{i1} + b_2 x_{i2} + \cdots + b_m x_{im} + E_i \ (i = 1, \ldots, n), \quad (1)$$

where E_i are independent and identically $N(0,s^2)$-distributed “errors”. b_0 is called “intercept” or “constant term” and the b_k*’s* $(k = 1, \ldots, m)$ are the (unknown) coefficients of independent (or impact or feature) variables X_k whose values x_{ik} are fixed (measuring points) having no random effect. Linear regression estimates these unknown coefficients $b_{1 \ldots m}$, and a suitable elimination procedure (here backward elimination) reduces the model’s complexity by removing effects whose contribution to the model is statistically “small”.

For each model-input-configuration (i.e. different sets of independent variables) a full model consisting of powers up to the 3rd of each variable is initially set up such that the “Ansatz” for modelling the target variable *Y* has the following form:

$$Y = b_0 + \sum_{i=1}^{\substack{N\ldots Number \\ of\ Parameters}} (b_{i1} X_i + b_{i2} X_i^2 + b_{i3} X_i^3). \quad (2)$$

This also accounts for possible non-linear relationships that can be embedded into linear regression by suitable transformation of impact variables (here polynomial). The backward elimination process (i.e. removing variables with reference to a suitable information criterion) has been carried through by using SAS 9.4’s proc reg-procedure with *selection=backward* (removal using Schwarz Bayesian information criterion) and *stay significance level = 0.001*. The final model is so to say an “optimized” construction regarding model parameters like number of observations, number of estimated parameters (i.e. number of independent variables in the model) and the probability that the observed data comes from a distribution, having parameter values equal to those estimated.

3.2 Database

The database for the linear regression model consists of the independent predictor parameters (or variables) from the tensile tests and the dependent variables, which are the minor and major strains for each FLC sample geometry.

3.2.1 Independent predictor parameters – Sheet thickness and tensile test data

For most FLCs, tensile tests from the corresponding metal sheets were done in longitudinal *L* and transversal *T* direction, according to the sheet rolling direction. Only tensile tests with a measurement length of 80 mm were used since the fracture strain depends on the measurement length, while the uniform elongation A_g is mor or less independent of the specimen geometry. The available FLCs cover the whole product range, for both evaluation methods, as Figure 3 shows.

The considered independent parameters are sheet thickness *Th,* yield stress R_{p02}, tensile strength R_m, uniform elongation A_g and fracture strain A_{80}, in *L* and *T* direction.

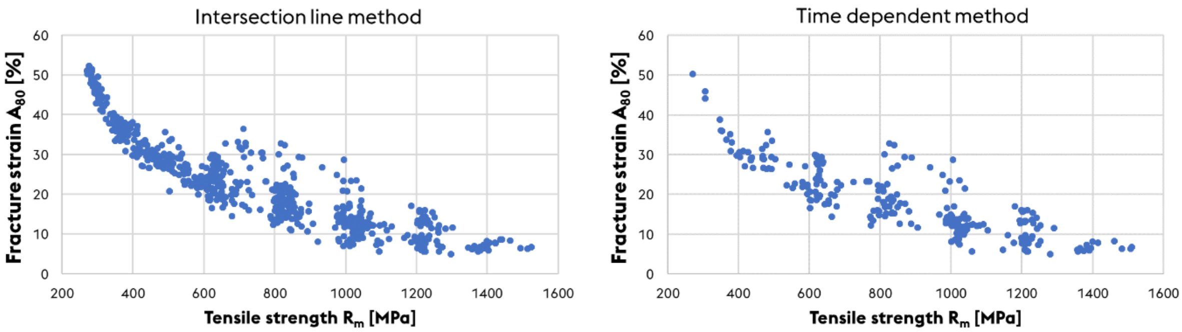

Figure 3: Fracture strain A_{80} versus tensile strength R_m corresponding to the available experimental FLC in the database, (left) for intersection line method FLCs and (right) for time dependent FLCs.

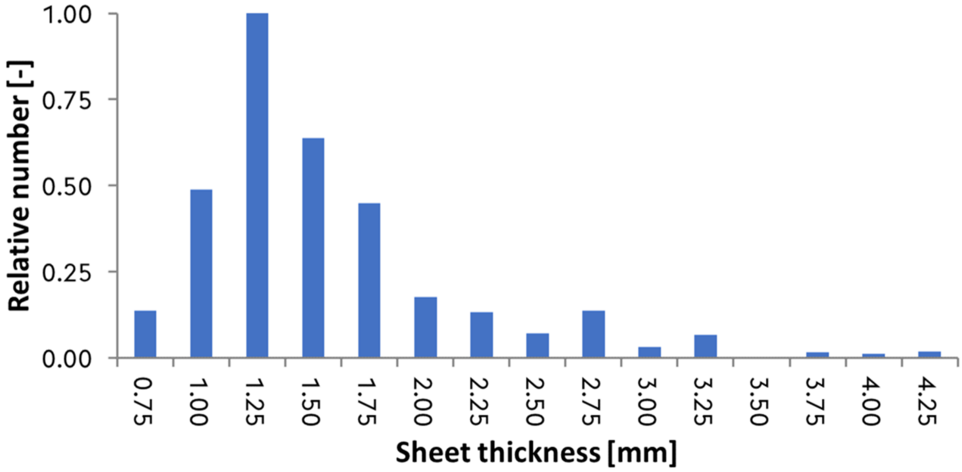

Figure 4: Sheet thickness distribution of available experimental FLCs.

3.2.2 Dependent variables – Minor and major strain values

The dependent variables are the minor and major strain values of the available FLCs. These FLCs cover a relevant thickness range from 0.6 mm to about 2.6 mm, as shown in Figure 4.

3.3 Model equation

After performing the linear regression with different sets of independent parameters, the respective values for d_0 and the coefficients $k_{n1...3}$ for equation 3 are available.

$$\varphi_i = d_0 + \sum_{n=1}^{\substack{Nr.\ of \\ Parameters}} \left(k_{n1}P_n + k_{n2}P_n^2 + k_{n3}P_n^3\right) \tag{3}$$

Equation 3 is just another form of equation 2, where φ_i is the major or minor strain of the individual FLC sample geometry, and P_n are the chosen independent parameters.

Additional Remarks: First, due to sparse data and the very similar geometry specimens 145 and 150 are combined and denoted with 147.5, like Schmid et al. 2012 [3]. Second, during model evaluation it became apparent, that a separation of the database in FLCs for steels with R_m < 750 MPa and R_m ≥ 750 MPa gives better results, therefore only models with this division, or classification, are presented in this paper.

4 Model results

Different model results, i.e. list of coefficient values for equation 3, were created to give the user the possibility to choose a suitable model. This decision can thereby be based on the availability of the tensile test parameters. The considered independent parameters are sheet thickness *Th,* yield stress R_{p02}, tensile strength R_m, uniform elongation A_g and fracture strain A_{80}, in longitudinal *L* and transversal *T* direction.

Results for the following models are available, where *Th* and the information if R_m is above or below 750 MPa is always necessary:

- *Th* and A_{80} – simple model, like Schmid et. al 2012,
- *Th*, R_{p02}, R_m and A_{80} – defined standard values, often supplied by test certificates,
- *Th*, R_{p02}, R_m, A_g and A_{80} – full strength and fracture dataset,
- *Th*, R_{p02}, R_m and A_g – dataset independent of tensile specimen geometry.

In this paper only the coefficient set for one model, i.e. intersection line method FLC based on *Th*, R_{p02}, R_m and A_g measured in transversal *T* direction, is included in Table 1. With equation 3 one obtains the minor and major strain values of the different specimen geometries, and with a e.g. a linear interpolation the complete FLC.

If we only consider this set of independent parameters in Table 1, there are double the number of coefficients if we also take the time dependent method into account, or four times the number if we also consider the longitudinal *L* test direction. So, to distribute the model and facilitate the use, an Excel template tool with coefficient sets for all regarded parameter sets is freely available upon request.

Table 1: Coefficient set for minor and major strain for intersection line method FLC, based on the independent parameters thickness Th, yield stress R_{p02}, tensile strength R_m and uniform elongation A_g in transversal T direction. Attention: Independent parameters R_{p02} and R_m scaled by 0.01 and A_g by 0.1.

Minor strain intersection line method

Geometry	R_m < 750 MPa	d_0	$k_{Th\,1}$	$k_{Th\,2}$	$k_{Th\,3}$	$k_{Rp02\,1}$	$k_{Rp02\,2}$	$k_{Rp02\,3}$	$k_{Rm\,1}$	$k_{Rm\,2}$	$k_{Rm\,3}$	$k_{Ag\,1}$	$k_{Ag\,2}$	$k_{Ag\,3}$
30	False	-0.10489	0.00777	0	0	-0.02813	0.00130	0	0.03386	-0.00125	0	-0.09388	0.01397	0
	True	-0.43848	0.01270	0	0	0.02595	0	0	0	0.01373	-0.00140	0	-0.01512	0
70	False	-0.08901	0.04152	-0.00820	0	-0.00781	0.00039	0	0.01583	-0.00061	0	0	-0.02336	0.00519
	True	-0.25472	0.01397	0	0	0.07565	-0.00782	0	0	0.00114	0	0	-0.01262	0
85	False	-0.06376	0.03263	-0.00526	0	0	0	0	0.00724	-0.00029	0	0	-0.00338	0
	True	-0.16871	0	0.00334	0	0.06134	-0.00653	0	0	0.00080	0	0	-0.00759	0
110	False	-0.07084	0.03721	-0.00543	0	0	0	0	0.00679	-0.00027	0	0.02184	-0.00498	0
	True	0.05199	0	0.01158	-0.00207	0.11739	-0.02352	0.00152	-0.13314	0.02440	-0.00145	0	0	0
125	False	-0.09277	0.02805	0	-0.00082	0	0	0	0.01037	-0.00042	0	0.06918	-0.03353	0.00657
	True	-0.02313	0	0.01207	-0.00200	0.07283	-0.01386	0.00076	-0.02319	0.00211	0	0	0	0
147.5	False	-0.95785	0.03199	0	-0.00085	0	0	0	0.23893	-0.02007	0.00055	0.07946	-0.00918	0
	True	0.15219	0	0.02393	-0.00468	0.25328	-0.05574	0.00361	-0.14415	0.01221	0	0	0	0
160	False	-0.00141	0.01347	0	0	0	0	0	0	0	0	0.10288	0	-0.01235
	True	0.45080	0	0.02659	-0.00569	0	0	0	-0.18079	0.01437	0	0.20913	0	-0.01791
R	False	0.29895	0.01753	0	0	0	0	0.00006	-0.01827	0	0	0.23372	-0.14359	0.03252
	True	0.37699	0.04917	0	0	0	-0.00386	0	0	0	-0.00009	0	0.00796	0

Major strain intersection line method

Geometry	R_m < 750 MPa	d_0	$k_{Th\,1}$	$k_{Th\,2}$	$k_{Th\,3}$	$k_{Rp02\,1}$	$k_{Rp02\,2}$	$k_{Rp02\,3}$	$k_{Rm\,1}$	$k_{Rm\,2}$	$k_{Rm\,3}$	$k_{Ag\,1}$	$k_{Ag\,2}$	$k_{Ag\,3}$
30	False	0.32876	0	0.00569	0	0.04788	-0.00215	0	-0.07818	0.00294	0	0.23026	-0.03976	0
	True	0.95876	0	0	0	0	-0.00269	0	-0.14765	0.00936	0	0	0.02099	0
70	False	0.19129	0	0.01077	0	0.00610	0	0	-0.03394	0.00111	0	0.14739	0	-0.00366
	True	0.61740	0	0.00803	0	-0.10018	0.01029	0	0	-0.00415	0	0	0.02945	0
85	False	0.23575	0	0.00991	0	0	0	0	-0.02942	0.00108	0	0.06756	0	0.00274
	True	0.55786	0	0.00893	0	-0.09608	0.01028	0	0	-0.00433	0	0	0.02428	0
110	False	0.07224	0	0.01899	-0.00229	0	0	0.00002	-0.00725	0	0	0.15722	-0.06357	0.01317
	True	0.64855	0	0.02199	-0.00328	-0.21123	0.04527	-0.00315	-0.02963	0	0	0	0.01437	0
125	False	0.03767	0.04817	0	0	0	0	0	-0.00482	0	0	0.16500	-0.07311	0.01599
	True	0.90266	0.05208	0	0	0	0	-0.00016	-0.34952	0.05583	-0.00306	0	0.00935	0
147.5	False	0.01439	0.04343	0	0	0	0	0	0	-0.00016	0	0.23033	-0.10808	0.02363
	True	0.52595	0.08102	0	-0.00175	0	-0.00221	0	-0.10216	0.00704	0	0.03921	0	0
160	False	0.11770	0.04042	0	0	0	0	0	-0.00786	0	0	0.17416	-0.04465	0
	True	0.78246	0.05020	0	0	0	-0.00436	0	-0.13975	0.01107	0	0	0	0
R	False	0.41530	0	0	0	0.01292	0	0	-0.02377	0	0	0.03774	0	0
	True	0.41093	0.05704	0	0	0	-0.00414	0	0	0	-0.00012	0	0	0.00267

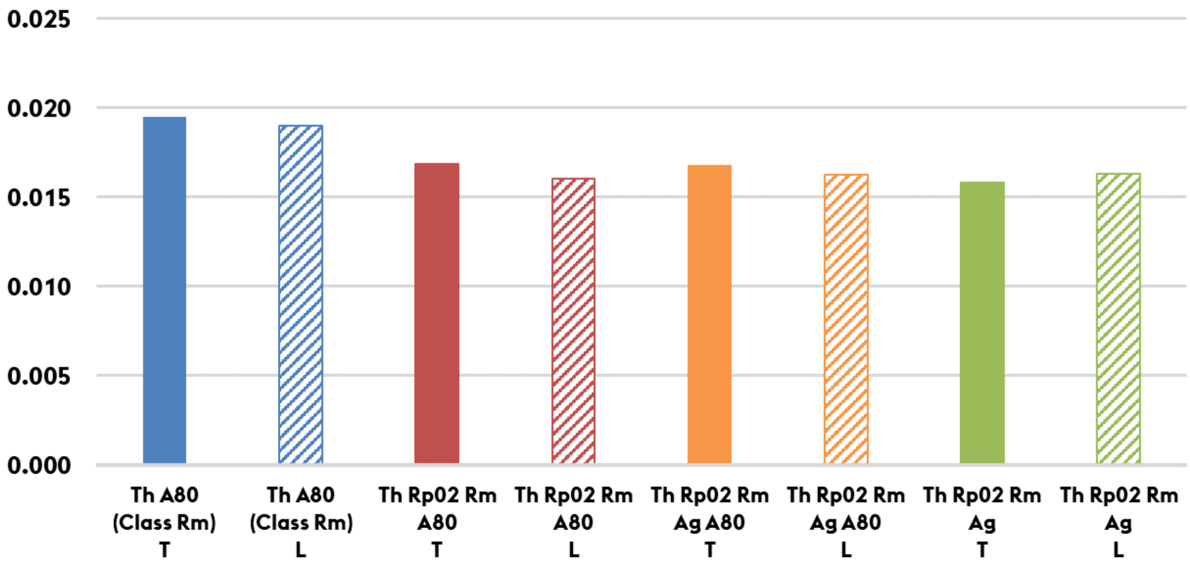

Figure 5: Mean absolute major strain deviation of the investigated models, based on the tensile test parameters thickness Th, yield stress R_{p02}*, tensile strength* R_m*, uniform elongation* A_g *and fracture strain* A_{80} *in longitudinal L or transvers T direction. (Class Rm) means the classification if* R_m *is above or below 750 MPa.*

5 Model evaluation

voestalpine provides a comprehensive set of material data for forming simulation to various solver developers and distributors. They create the material cards for their users. A set of material cards for LS-Dyna is available on request from voestalpine and DYNAmore. We used the current dataset of FLCs to evaluate the models, 102 intersection line method FLCs and 35 time dependent FLCs, or 113 FLCs for cold rolled and 24 for hot rolled steel sheets. It should be noted that we also used this FLCs for the regression models, since we did not want to exclude this high number of FLCs from the coefficient determination!

Quantitative evaluations were conducted, one example is shown in Figure 5. It depicts the mean absolute major strain deviation between model FLC and experimental FLC. The conclusion of these quantitative evaluations is that the simple model with the independent parameters *Th* and A_{80} shows a slightly lower performance than the models which also take R_{p02} and R_m into account.

Qualitative evaluations, like shown in Figure 6 for the model with the independent parameters *Th*, R_{p02}, R_m and A_g, illustrate the capabilities of the models.

The conclusion of the evaluation is our recommendation for the model based on *Th*, R_{p02}, R_m and A_g since it is independent of the tensile test specimen geometry and shows accurate and stable results. But all models which include stresses (R_{p02} and R_m) show similar results. The models should be used for a thickness range between 0.6 and 2.6 mm.

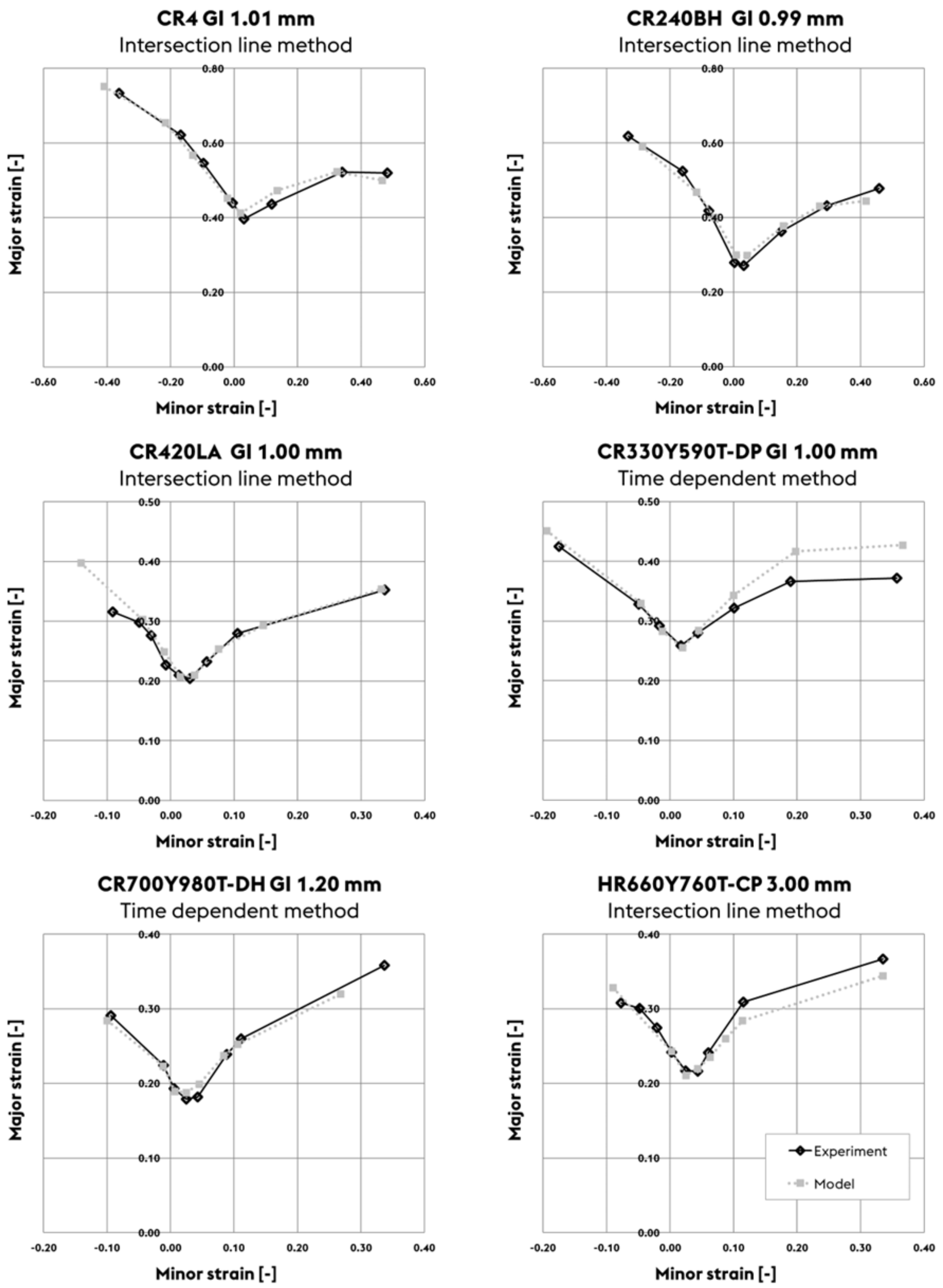

Figure 6: Comparison of various experimental FLCs with the model results, model FLC based on thickness Th, yield stress R_{p02}, tensile strength R_m and uniform elongation A_g in transversal T direction.

6 Summary

The presented regression model results can describe the experimentally measured FLCs for intersection line and time dependent evaluation. Depending on the available tensile test results a suitable parameter set can be chosen. We recommend using thickness *Th*, yield stress R_{p02}, tensile strength R_m and uniform elongation A_g, since it is independent of the tensile test specimen geometry. If A_g values are not available, use a model with A_{80} instead.

The applicable thickness range is 0.6 to 2.6 mm, above this range the results should be considered carefully.

Only one set of parameters is included in this paper. The other parameter sets are distributed freely in form of an Excel template upon request.

In conclusion, it should be noted that the presented method can simply be updated. Following the ongoing steel development and accompanying expansion of the FLC database, it only takes relatively little time and expense to create an updated set of model coefficients. This allows the model to be kept up to date!

7 Literature

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