Towards an Automatic Evaluation of a Car Floor Module in a Pole Crash Load Case

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Abstract

Nowadays crashworthiness simulations are regarded as not suitable for optimization. One reason is the lack of hard evaluation criteria. A small part of the evaluation of crashworthiness simulations is done by comparing numerical criteria to given boundaries. The larger part of the evaluation consists of visual evaluation based on engineering experience. This visual evaluation on the one hand contains the influence of the engineer's subjective perception, which endangers the quality and the reproducibility of the overall evaluation. On the other hand, those visual criteria cannot be evaluated automatically and, thus, make the use of them as restriction in a weight optimization impossible. With the example of the full vehicle simulation of the ARENA2036 project lightweight through integrated functions in the pole crash load case, the manual visual evaluation has been analyzed. Therefore, only geometry and displacement of LS-DYNA® d3part files containing the car floor module of several variants have been presented to 45 crashworthiness simulation engineers, who had to evaluate and rank those variants. Based on this analysis, evaluation patterns have been deduced. The possibilities to analyze those patterns automatically, with either an analytical analysis or image analysis, have been checked. The most promising alternative has been implemented, which generates additional numerical output parameters based on the existing LS-DYNA output files. Those parameters have been compared to the feedback given during the manual evaluation, to check to what extent the analysis can be automated and, thus, which criteria can be used as restrictions in a weight optimization based on LS-DYNA models.

Introduction

Optimization is an established method for systematic problem solving. It is widely known, that the development of optimization algorithms for theoretical problems can face challenges with real world problems by the means of computing time and robustness. Especially regarding weight optimization of crashworthiness simulations a third problem occurs. For the weight optimization requirements regarding the crash performance have to be taken into account as restrictions. Nowadays the evaluation of crashworthiness simulations consists of hard and soft criteria. The hard criteria are given as numerical parameters, like intrusion, and can, thus, be easily evaluated automatically. The soft criteria, like structural integrity, get evaluated visually based on engineering experience. Those soft criteria cannot be evaluated automatically. Furthermore, they endanger the reproducibility and, therefore, quality of the evaluation, since a visual evaluation by a human does not only contain objective evaluation patterns, but also the subjective perception of the engineer in charge. This paper is based on a preliminary work, analyzing the manual evaluation of different variants of the same car by several engineers. The deduced evaluation patterns will be formalized including scaling and weighing parameters. The evaluation algorithm will be implemented in a prototypical evaluation tool and the results, depending on different scaling and weighing parameters will be generated. Those results get compared to the results of the manual evaluation.

Preliminary Work

As pointed out in [1], the analysis is based on the concept of the ARENA2036 project lightweight through integrated functions [2], using the pole crash LS-DYNA model of the second crashworthiness evaluation loop. The concept of the composite-foam-sandwich is shown in figure 1.

Figure 1: ARENA2036 lightweight through integrated functions concept [2]

15 variants have been created based on this model. The variants differ in the stacking of the main floor top layer, the stacking of different sections of the beam cross member and an optional existence of a partial foam core in the front beam cross members.
Those variants have been analyzed manually by 45 engineers from 6 different companies as shown in [1]. Figure 2 shows the statistic results of the ranking positions given in the manual evaluation. Figure 3 shows the percentage of engineers agreeing on the variants failing or passing the evaluation in general.

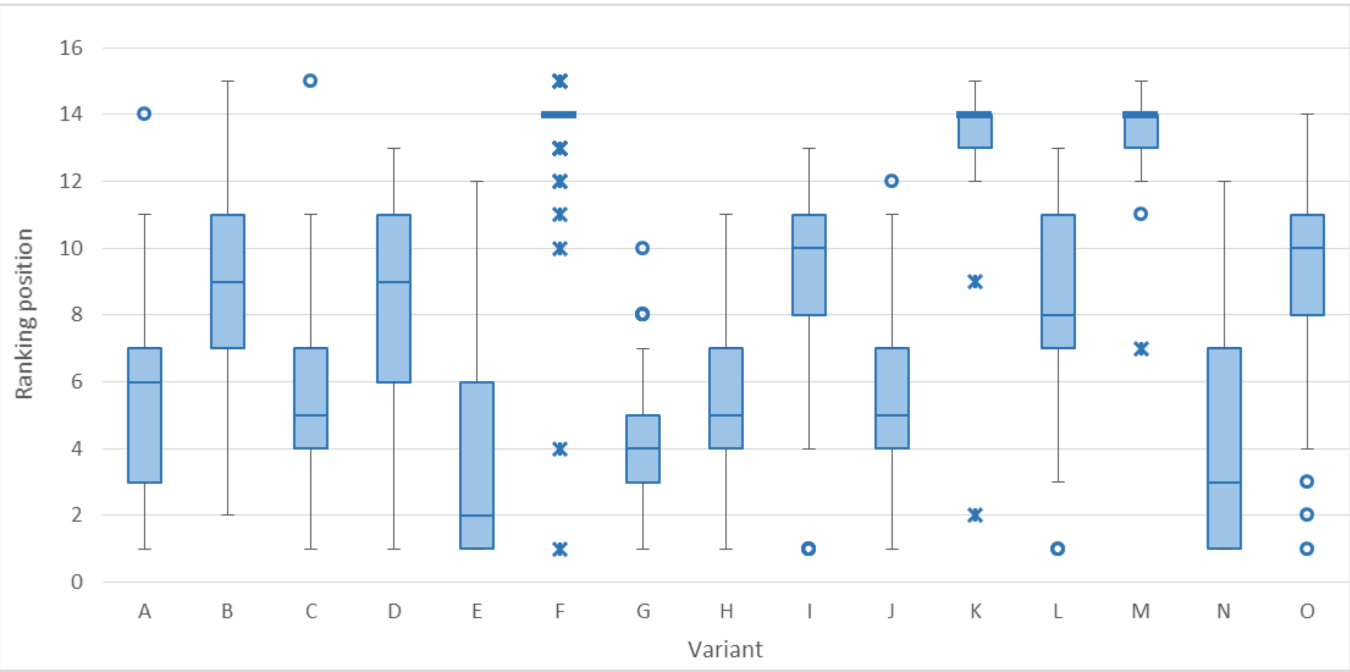


Figure 2: Box plot – Ranking positions of each variant, manual evaluation [1]

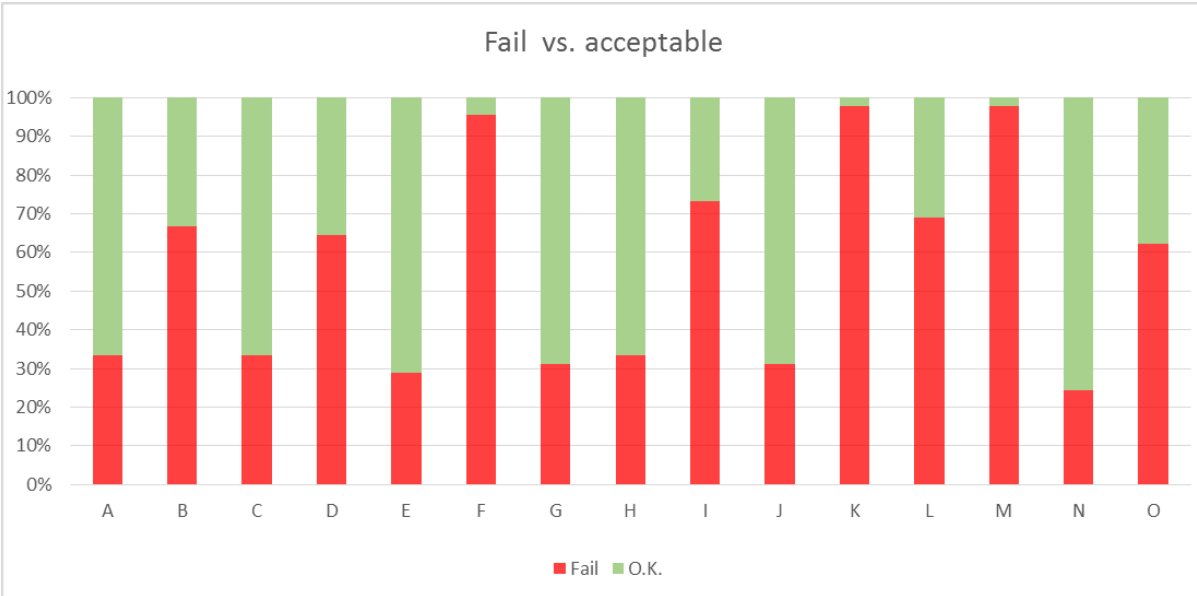


Figure 3: Fail vs. acceptable of each variant, manual evaluation

The manual evaluation has been used to deduce evaluation pattern for an automated evaluation.

Evaluation Patterns for Material Failure

Material failure or the existence of cracks are displayed by deleted elements in the visual post processing data. Therefore, the automatic evaluation of material failure can be done by analyzing the failure value of each element. A failure value of one means that the element completely failed and has been deleted. Besides the amount of failed elements, their relation and their position also plays an important role in the evaluation. To take into account the relation of all failed elements of one part, first of all, groups of failed elements, which share at least one edge, have to be identified. In each group every single element gets evaluated on its own, regarding the relation they have to other failed elements. For this three different strategies have been analyzed. Strategy one counts the failed elements sharing a node disrespecting the failed element the analysis is done for and sums up this result for all nodes of the element.

$$FI_{Crack,n,y,S1,i} = \sum_{j=1}^{N_N} N_{fE,j} - 1 \quad (1)$$

Strategy two counts the number of nodes, which are shared by another failed element:

$$FI_{Crack,n,y,S2,i} = N_{NfE} \quad (2)$$

Strategy three counts the number of neighboring failed elements, which means elements that share an edge with the regarded element:

$$FI_{Crack,n,y,S3,i} = N_{fEN} \quad (3)$$

For all strategies the value of all single elements (i) will sum up to the crack value of the element group:

$$FI_{Crack,n,y} = \sum_{i=1}^{N_E} FI_{Crack,y,i} \tag{4}$$

Table one shows the results of all different strategies for simple examples with the same number of failed elements (orange):

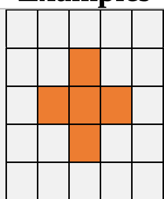
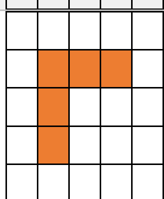
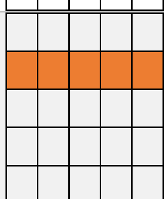
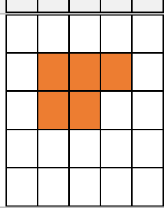
Examples	Strategy one	Strategy two	Strategy three
	24	12	8
	18	15	8
	16	16	8
	26	15	10

Table 1: Fail vs. acceptable of each variant, manual evaluation

These examples clearly show, that strategy three is not suitable to evaluate material failure based on its shape. Strategy two sees an area of failed elements more critical when it is line shaped, while strategy one evaluates an area of elements more critical the more it fills up a 2-dimensional area. Since the preference of these two strategies does not get clear by the preliminary work, both strategies will be used for the automatic evaluation.

$$FI_{Crack,n,y} = g_S \sum_{i=1}^{N_E} FI_{Crack,y,S1,i} + (1 - g_s) \sum_{i=1}^{N_E} FI_{Crack,y,S2,i} \tag{5}$$

$$g_S = [0;1] \tag{6}$$

Besides the shape, the criticality of a failed area also depends on its position in the vehicle. In our case, the pole load crash, the position regarding the closeness to the sill and, thus, the y-coordinate is the only direction that matters:

$$FI_{Crack,n} = g_y \left(g_S \sum_{i=1}^{N_E} FI_{Crack,y,S1,i} + (1 - g_s) \sum_{i=1}^{N_E} FI_{Crack,y,S2,i} \right) \tag{7}$$

The scaling factor g_y depends on the average y-position of all failed elements of the group, with

$$g_y = [0;1] \tag{8}$$

$$y_{in} < y < y_{out} \tag{6}$$

Whereat y_{in} is the y-coordinate at the tunnel and y_{out} is the y-coordinate at the sill. The middle position between the sill and the tunnel is always regarded as most critical, since this is the occupant's position:

$$g_{y,mid} = g_y \left(\frac{y_{in} + y_{out}}{2} \right) = 1 \tag{9}$$

It is supposed, that g_y changes linear between y_{in} and y_{mid} as well as in between y_{mid} and y_{out}:

$$g_y = \begin{cases} \dfrac{2(1 - g_{y,in})(y - y_{in})}{y_{out} - y_{in}} + g_{y,in} & y < \dfrac{y_{in} + y_{out}}{2} \\ \dfrac{(1 - g_{y,out})(2y - y_{out} - y_{in})}{y_{out} - y_{in}} + g_{y,out} & y > \dfrac{y_{in} + y_{out}}{2} \end{cases} \tag{10}$$

The crack value over all failed element groups (n) can be determined by summing up all single crack values:

$$FI_{Crack} = \sum_{n=1} FI_{Crack,n} \tag{11}$$

Evaluation Patterns for Bending and Buckling

The automatic evaluation of bending is done by analyzing the relative displacement of the nodes. For the example of a car floor module the displacement in z-coordinate, which means upward or downward bending, is of note. In the first step the z-coordinates $z_{N,0}$ of all nodes of the considered part in state zero get excerpt. The z-coordinates of each state get compared to these values, to determine the absolute displacement:

$$l_{N,t,abs} = \left| z_{N,t} - z_{N,0} \right| \tag{12}$$

To determine the relative displacement, the value gets compared to the minimum value of all nodes:

$$l_{N,t,rel} = l_{N,t,abs} - l_{\min,t,abs} \tag{13}$$

The failure value regarding relative displacement of nodes in one part is given by the maximum relative displacement value:

$$FI_{Bend} = \max\left(l_{N,t,rel}\right) \tag{14}$$

A positive relative displacement of nodes in one part can either occur due to bending or buckling. While bending is critical by the means of changing the load path in way that it is not pointing at its target point directly, buckling is even worse, since the original load path is completely destroyed and there will be a sudden change of the gradient in the force-deflection-function. Therefore the change of displacement in each time step will be compared to the one before and a maximum tolerance value depending on the number of states and the number of nodes of that part for the difference between bending and buckling will be set. Additionally a tolerance is needed, so that impacts of material failure do not lead to wrong results.

$$\Delta l_{N,t} = l_{N,t,rel} - l_{N,t-1,rel} \tag{13}$$

$$d_{\Delta l,N,t} = \frac{\Delta l_{N,t}}{\Delta l_{N,t-1}} \tag{14}$$

$$d_{\Delta l,N,t,Buckling} = d_{\Delta l,N,t} > \frac{N_{Nodes} N_{States}}{V_{Buckling}} \tag{15}$$

$$d_{\Delta l,\max} = \max\left(d_{\Delta l,N,t}\right) \tag{16}$$

$$g_B = \begin{cases} 1 & d_{\Delta l,\max} < \dfrac{N_{Nodes} N_{States}}{V_{Buckling}} \\ g_{Buckling} & d_{\Delta l,\max} > \dfrac{N_{Nodes} N_{States}}{V_{Buckling}} \wedge N_{d_{\Delta l,N,Buckling}} > \dfrac{N_{Nodes} N_{States}}{V_{Security}} \end{cases} \tag{17}$$

$$g_{Buckling} = [1;10] \tag{18}$$

$$V > 1 \tag{19}$$

Thus, the overall failure value regarding bending and buckling can be described as:

$$FI_{BB} = g_B FI_{Bend} \tag{20}$$

Overall evaluation of car floor module

Based on [1], the overall evaluation of the car floor module in the pole crash can be done by evaluating material failure, bending/buckling and failure of joints:

$$FI = g_{Crack} FI_{Crack} + g_{BB} FI_{BB} + g_{Det} FI_{Det} \tag{21}$$

with

$$g_{Crack} + g_{BB} + g_{Det} = 1 \tag{22}$$

Since at the time of this writing the automatic evaluation of the failure of joints is still in progress, the automatic evaluation in this paper has been done only regarding material failure and bending/buckling:

$$FI_{red} = g_{Crack,red} FI_{Crack} + (1 - g_{Crack,red}) FI_{BB} \tag{23}$$

Prototypical Evaluation Tool

To validate the theoretical evaluation patterns, (1) to (23) have been implemented in a prototypical evaluation tool. This tool has been created using Java, since this only requires the installation of Java virtual machine to run the program and, thus, creates a cross-platform tool. Additionally, the tool accesses the post-processing tool Animator 4 for the analysis of bending and buckling. At first, the d3inp and all included files get analyzed, to store the information of the initial status. One part of this process is storing all parts with their corresponding elements and nodes. For the analysis of material failure the all_mes file is also needed. This file contains the information about the element-IDs of all failed elements. With this information all failed elements belonging to one part in the previously saved list get filtered. Subsequent to that, the list gets analyzed regarding duplicate node-IDs. With this information neighboring failed elements, that share at least one node, get identified as part of one group. For bending and buckling a list of all coordinates of all considered nodes at all time steps is generated by Animator. Afterwards all information will be processed as described above. The implementation of the automatic evaluation of failure of joints is still pending at the time of this writing and will be include later on.

Results

Since Variant F, K and M have been the variants which have been evaluated as the worst variants due to a buckling of the front beam cross member on the driver's side and the floor and B, D and O as the second worst due to a buckling of the floor, the value for $V_{Buckling} = 636{,}55$ and $V_{Security} = 25{,}385$ could be easily determined. For all scaling and weighing factors g different combinations of 0.0, 0.5 and 1.0, and respectively 1.0, 5.0 and 10 for $g_{Buckling}$ have been tested. Those factors will give a hint as to what extend the single evaluation strategies play a role at all. A precise determination of the correct factors will be done as soon as the failure of joints is included. For the further presented results, the combination of scaling and weighing factor have been used, which led to the smallest deviance between the ranking positions given by the automatic evaluation and the median of the ranking positions given in the manual evaluations. Figure 4 shows the statistic results of the ranking positions given in the manual evaluation compared to the ranking positions given by the evaluation tool.

Those ranking positions have been created by 44 different combinations of the scaling/weighing factors. All those combinations included $g_{Buckling} = 1.0$. This states that it is not that important, whether it is bending or buckling, since an evaluation based on the non-time-dependent relative displacement is sufficient. For $g_{Crack,red}$ the combinations includes values of 0.0 and 0.5 with an average over all combinations of 0.2. This shows, that bending/buckling seems to be more critical than material failure. Nevertheless, material failure should still be considered. For all other scaling factors, the combinations included 0.0 as well as 0.5 and 1.0. While there is no clear evidence, what value to pick for $g_{y,in}$ and $g_{y,out}$, $g_S = 1.0$ only leads to good results in those combinations including $g_{Crack,red} = 0$, which eliminates the influence of g_S. This is a clear evidence, that strategy two is more suiting for evaluation material failure than strategy one. The exact value has to be determined. So far, both strategies will be kept. The combination of the factors $g_{y,in}$ and $g_{y,out}$ did not show a severe difference in the results. For now, the position of the crack does not seem to play such an import role. Since this could depend on the chosen example, the possibility to rate the crack based on its position will be kept for future evaluations. It will be set to $g_{y,in}=1.0$ and $g_{y,out}=0.5$ due to the statement of several engineer, that a damage is never requested, but at the utmost acceptable close to the sill.

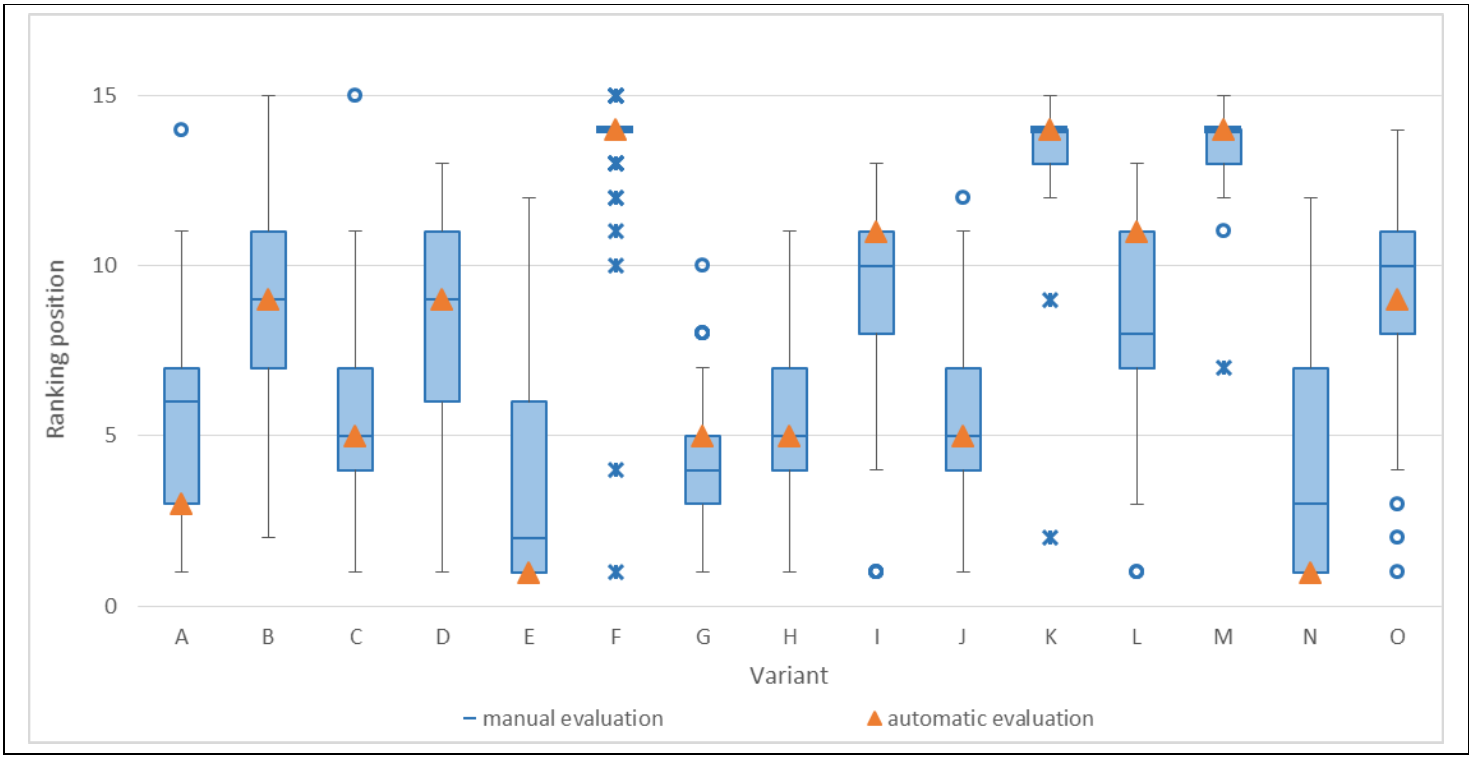


Figure 4: Ranking positions of each variant, manual evaluation vs. automatic evaluation

In general the results show a high conformity. For eight variants the median of the ranking positions given in the manual evaluations are exactly the same as the ranking positions given by the automatic evaluation. For seven variants the ranking position given by the automatic evaluation lies in between the box of the boxplot, which means the area of ranking positions 50% of the engineers agreed on. Figure 5 shows FI compared to the percentage of engineers agreeing on the variant failing or passing.

Since g_S, $g_{y,in}$ and $g_{y,out}$ are only taken into account for $g_{Crack,red}>0$, 27 of the 44 combinations lead to the same results. The green line shows the FI when only bending is taken into account. The result fit quite well. Only small differentiations, like between Variant A and C cannot be done using only bending. Comparing the results of $g_S=0.0$ (red/yellow lines) and $g_S=0.5$ (blue lines) it gets clear, that it leads to different results, which, however, are not crucial for this example. The same applies for $g_{y,out}$ and $g_{y,in}$. The different values for $g_{y,in}$ nearly always lead to same results, except of in variants E, I, L and N, which just makes clear, that all other examples didn't show any material failure close to the tunnel and that even in variants E, I, L and N only few elements fail.

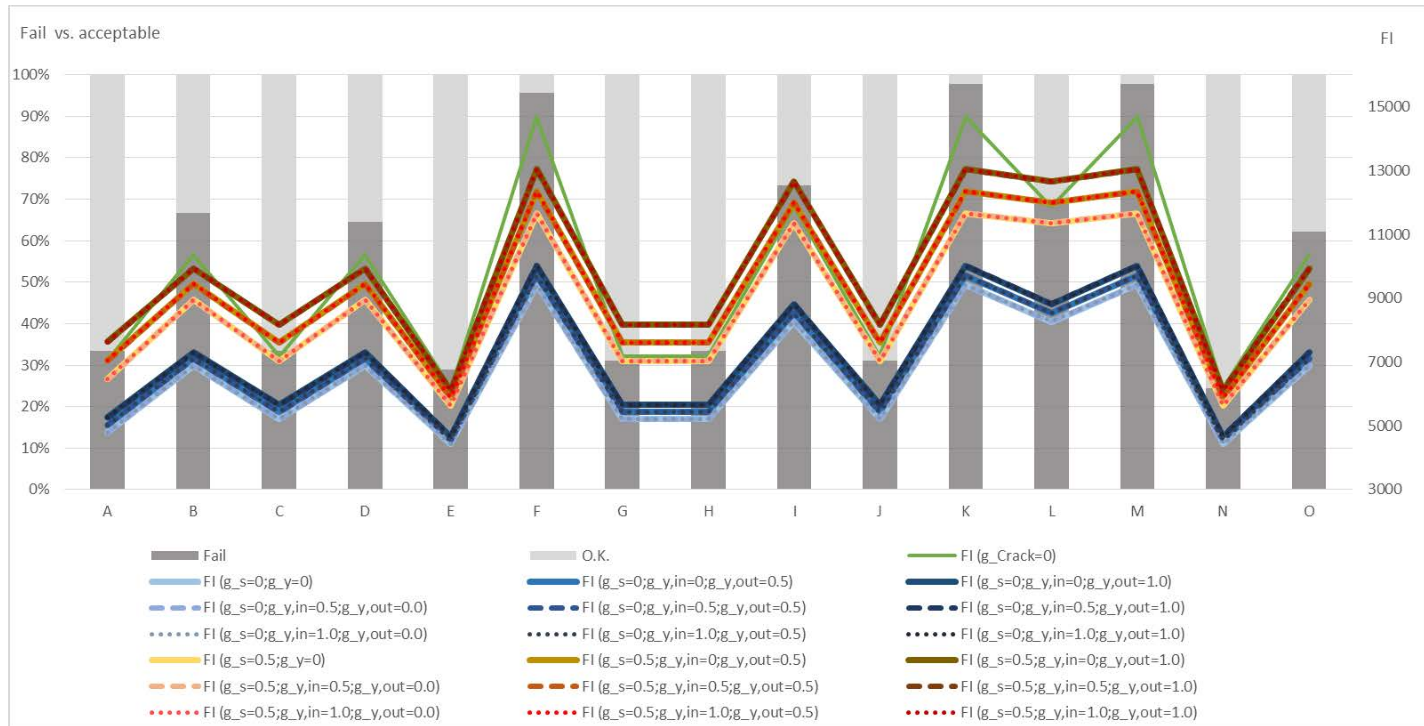


Figure 5: Fail vs. acceptable, manual evaluation vs. FI automatic evaluation

Conclusion

As already stated in [1] an automatic evaluation is strongly recommended, since the variance of the manual evaluation is too high. The work of this paper shows, that an automatic evaluation of material failure and bending/buckling is possible. Nevertheless, it shows that, even though some criteria seem to be sufficient for several examples, for a complete correct evaluation all criteria are needed. Therefore, optimizations only based on several criteria, such as intrusion, do not necessarily give out the optimal design. If the worst comes to the worst, it could even lead into a completely wrong direction regarding the input parameters. In the next step, the failure of joints will be included and suiting parameters for the scaling and weighing factors will be derived.

References

[1] Diermann, V., Kahn, K., & Middendorf, P. (2017, November). Towards a multidisciplinary optimization of a body in white including whole vehicle crashworthiness load cases: The complexity of automated evaluation shown on the example of a beam cross member. Proceedings of the 33rd International CAE Conference, Vicenza, Italy, 2017.

[2] Vohrer, Sebastian, et al. "Funktionsintegrierte Faserverbundstrukturen im Fahrzeugbau." Tagungsband LLC 2017 (2017): 198-208