Influence of single hat crash box flange triggering and impactor top plate welding strategy on axial crash foldability of AHSS & UHSS sheets

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Abstract. Axial crash tests are usually performed in order to assess the crash foldability of AHSS & UHSS sheets in the framework of a material homologation process. With a real component like single hat column geometry with RSW flange welded and MAG welded top/down head plates crash box design, it is getting more and more difficult to assess properly the crash performance of AHSS & UHSS steel grades with tensile strength $R_m \geq 1000$ MPa (RSW: resistance spot welded, MAG: metal active gas welded). The crash box flange is namely excessively stiff and prevents the initiation of a proper crash-folding pattern, resulting in a high amount of material failure, which makes some judgement about material crash ability difficult. Therefore the present experimental investigation focuses on the one hand on the triggering strategy in the top flange area to break the excessive stiffness of the spot-welded flange. On the other hand some effort has been put in the improved joining strategy of the top impactor head plate to the crash box itself. The top head plate is usually necessary in real components for load transfer to the crash box and fixation to the surrounding body in white structure. Some excessive welding of the top impactor plate, especially in the already largely stiffened spot-welded flange region, has however a strong detrimental effect on crash fold initiation. The welding of the top head plate in the flange and back crash box areas is avoided, thus increasing the degrees of freedom between top impactor plate and crash box column along with an effective reduction of the initial crash box bending stiffness. Some minimized welding of impactor plate to the crash box column, especially avoiding flange areas, allows a successful initiation of the crash folding process but only in combination with pressed round triggers in the flange area near the first spot weld. With these modifications it is first possible to assess and rank the intrinsic axial crash foldability of the material with $R_m \geq 1000$ MPa by means of a crack length based crash index.

1. Introduction
Increasing demands on improvement of passenger safety and mass reduction has led to an increased application of high strength steels in the automotive industry. Material selection during the design of crash-relevant structures has become a challenge due to the variety of available advanced high strength steels (AHSS) and ultra-high strength steels (UHSS). Crash tests on the desired automotive body components might deliver some insights but are typically not feasible due to the lack of a final design and tools to manufacture these components. Thus small-scale model crash tests have been established during material homologation. The axial crash test of crash boxes has become a benchmark test when it comes to testing crashworthiness of sheet materials. In order to exploit the lightweight potential of AHSS
in crash absorbing structures and to get comparable results, a regular folding mode should be ensured as it promises a high level of energy absorption and minimizes the risk of material cracking.

Regular folding modes can be accurately assessed by using the parameters introduced in [1] in a superfolding element approach to describe idealized folding mechanisms of corner elements and further specialized for top-hat sections in [2]-[5]. The prerequisite for regular folding top-hat sections is a suitable material-geometry combination and an optimized spot weld position. The geometry parameters need to be adjusted to the material in order to generate a stable and regular folding behavior. The critical stress should exceed the material yield strength to obtain crash profiles folding regularly in a progressive buckling mode and avoiding global buckling and folding irregularities [6].

The material-geometry optimization of voestalpine top single hat axial crash sample has been performed accordingly in [7]-[11] for AHSS with a tensile strength steel grades with 1.5 mm thickness by comparing successively the global buckling load (which is a function of the crushing distance) and the mean crushing force (which remains constant during the crushing process). Some guidelines criteria, such as the maximum initial length of a profile (shorter), are resulting in order to avoid a mode change during the crushing process and ensure a regular folding mode. The crash box thickness to width ratio has also to be increased to take into account the higher yield strength level and ensure a regular folding pattern. This leads necessarily to smaller sample cross sections if the same thickness range around 1.5 mm is to be tested.

Closed hat cross-sections have been established as a standard test, using both trapezoid hat [11]-[13] as well as 90° rectangular hat [2],[14],[15] profiles. Hexagonal [16] or even 12 sided [17],[18] samples shapes can also be found in the literature. Asymmetric close single hat with back plates as well as symmetric double hat crash box shapes can be found. Usually the flange is resistance spot welded. Alternatively flangeless samples also exist, either laser [16],[17] or MIG (metal-inert-gas) welded [18].

Profiles may be tested with or without impactor plates, which are typically MAG welded to the top and bottom of the profiles mimicking the assembly of crash boxes in the automotive body. Therefore if an impactor head plate is used in the tests, it is fully welded to the profile along its full circumference.

The goal of a trigger in an axial crash box is to promote a progressive folding pattern and to lower the occurring peak force below a level which might induce global Euler-type buckling of the whole column. Different trigger mechanisms are reported in literature. Triggering can either be performed with self-triggering tapered columns [5],[17] or via localized laser heat treatment [16],[19] or by means of holes & slots cut into the profile [17],[20],[21]. Some initial trigger deformations can also be coined with cutouts or half/full dents or grooves into the profile as reviewed in [22] and commonly found in axial crash investigations of automotive steel grades [14],[15].

2. Experimental procedures
Figure 1 shows the axial crash test set up operated as a horizontal crash unit to perform axial and bending crash tests on components. Axial crash tests are typically performed with a 283 kg impactor at speed up to 30-40 km/h. The sample is fixed to the bottom wall with 4 clamps. The whole crash test is documented with a high speed camera (6600 frames/s by full resolution 800x600).

The up to date voestalpine axial crash box geometry is described in [13] based on recommendations in [10]. As shown in Figure 2 it is based on a closed single hat crash box geometry with $\phi 7.5$ mm spot welds (30 mm weld pitch) joining the upper U-shaped shelf with the lower cover back sheet of same material and same thickness. 3 mm upper impact and lower bottom head plates are also MAG welded to the crash box, the bottom head plate being then rigidly fixed in a clamping device.

The initial sample height $L$ is reduced to 300 mm to minimize global buckling effects. The cross section is smaller than usual to ensure a regular progressive folding pattern. The fixed constant geometric parameters in this axial crash box (whatever thickness) are highlighted in Figure 2 with 44 mm for top-hat width, 46.1 mm for top-hat height and 98.3 mm for lower plate width. The cold bent radius $R$ is fixed to 6 mm with a 96° angle (> 90° trapezoid cross section geometry). The triggers are pressed on both sides (5 mm radius) around the first spot weld point in the flange area 15 mm from upper plate.
The 3 mm top head plate of the sample is lightly joined with only two 20 mm MAG welding lines on each wall side without welding on the flange itself or on the back (Figure 2). It increases the degrees of freedom in relative movement of the crash box upper edge beneath the head plate. This promotes a proper bending initiation of the first crash fold in combination with the flange-triggering close to the impact head plate. The lower plate on the bottom clamped side is welded more rigidly on 5 locations including flange areas.
The crash folding ability of investigated AHSS & UHSS steel grades is quantified by means of the so called crash index, which quantifies the damage on crash boxes based on observed crack length and amount (outside and inside inspection) after testing as described in [12], [13]. It has been introduced for axial crash evaluation of automotive steels [23] and also used for aluminum automotive grades [24].

Figure 3 gives a detailed description of the crash index threshold values used within this investigation, depending on the observed maximum crack length level on impacted axial crash boxes after testing. The previously described geometry optimization for progressive buckling (smaller, shorter) in combination with triggering and light top hat welding strategy chosen avoids successfully the occurrence of such massive splitting & curling type of damage pattern.

| Crash box damage | Crack length L | Axial crash index | Remark |
|------------------|----------------|-------------------|--------|
| no cracks        | L ≤ 0 mm       | 100               | no damage |
| 1 crack          | L < 10 mm      | 95                | small cracks |
| > 2 cracks       | 10 mm < L ≤ 25 mm | 70 | intermediate cracks |
| 1 crack          | L ≥ 25 mm      | 45                | large cracks |
| > 2 cracks       | crack length over entire fold | 35 | fold breaks |
| 1 curl           | "banana peel" initiation | 15 | Splitting & curling beginning |
| > 2 curls        | 10             | 10                | Fall splitting and curling |
| Crashbox fully curled | 5      |                    |        |
| Crashbox global buckling | 5 |                    |        |
| Crash box slipped away | 0 |                    | massive damage / test invalid |
| Crash box multiple breaks | 0 |                    |        |

Figure 3: Definition of crash index for axial crash tests.

3. Experimental results
The first development step consists in optimizing the crash box geometry for a reliable achievement of progressive buckling at the desired 1000 MPa tensile strength level as shown previously in Figure 2. It is then necessary to apply triggers in order to avoid a random crash folding initiation in the middle or bottom part of crash box outside the high speed camera focus. Triggering alone however will not be enough to initiate a regular folding pattern. For this purpose the upper head plate should not be too rigidly fixed (or even eliminated) for a proper folding initiation as illustrated in the next Figure 4.

Figure 4 shows some high speed snapshots of axial crash tests with the crash box geometry described in Figure 2 using the same 1000 MPa material. The initial configuration is performed without trigger and with a fully welded cross section on impact side between plate and crash box section (Figure 4a). The crash folding cannot initiate properly since the crash box is too stiff under the top impact plate, which results in the crash box tearing apart itself with splitting & curling initiation and poor crash index values instead of the intended progressive buckling.

Figure 4b shows another strategy without impact head plate at all. The folding pattern changes completely into an almost perfect progressive buckling mode even without triggering with much higher crash index level even at high crushing distance. Figure 4c shows in this case that the crash box upper edge slides and bends freely under the impactor plate initiating a progressive folding mode right away. Additionally the spot welds are also stabilised by being squeezed with minimal damage between the building folds in a compressive mode instead of being sheared apart as in Figure 4a.

Figure 4d shows the chosen current crash testing strategy. The impact head plate is kept but only joined on both sidewalls of the crash box away from the flange regions. This is enough to keep the impact plate in place during crash test ensuring a defined load contact with impactor but this still allows a free movement of the upper crash box edge beneath the impact head plate for proper progressive buckling initiation. The variety of crash index obtained is a function of crushing distance ΔH but also mainly of crash design, whereas the joining method of the head plate together with additional triggering has a dominating influence on final crash test result.
Figure 4: Crash folding mechanisms with/without top hat plate & with/without trigger, high speed video snapshots (same 1000 MPa steel grade for all test series).

Figure 5 shows some comparisons considering the axial crash behavior for 1200 and 1400 MPa steel grades with previous testing configuration (no trigger, head top plate rigidly welded) versus the new one (trigger & lightly welded head top plate on impact side). The crash box geometry is the same as described in Figure 2 but with different triggering and head plate MAG welding strategies.

Some striking improvement in foldability can be observed for the same material just by using the new triggering and head plate welding method. Higher crushing testing distance ΔH can be achieved with the new design, still allowing some differentiation using crash index as no curling occurs.

The new crash geometry is mainly optimised for 1000-1200 MPa tensile strength level around 1.5 mm. Even after applying triggers and head plate welding connection, some limitations can still occur for very thick (> 2 mm) or thin (< 1 mm) or UHSS materials (Rm ≥ 1300 MPa) with regard to the crash foldability with the proposed crash box geometry.
Figure 5: Axial crash folding behavior of 1200 MPa (left) & 1400 MPa grades (right) with/without trigger and optimized top hat welding (same grade for each testing configuration).

Figure 6 shows some typical axial crash results with the new crash box geometry with optimised trigger and light head plate welding strategy in the tensile strength range between 600 and 1200 MPa for typical AHSS and UHSS grades. High regular folding crushing deformations up to 50% of initial sample length (300 mm) and beyond can be achieved with this new sample geometry.

A differentiation between the investigated grades can still be achieved via the crash index parameter. Instable buckling as well as split & curling effects or spot weld point failure can be eliminated, which hence still enables a proper lightweight potential analysis and damage crash index ranking of automotive steel grades with tensile strength $\geq$ 1000 MPa.

Figure 6: Crash box folding behavior exemplary of 600, 800, 1000, 1200 MPa steel grades with new optimized crash box geometry (with trigger & light top hat plate welding).
4. Conclusions
Crash energy absorption capability of AHSS and UHSS grades can only be assessed if the axial crash geometry does not show any unstable buckling mode as well as splitting and curling effects. Crash box samples must be designed smaller in cross section and shorter in length to accommodate for increasing strength level. A triggering in the spot welded flange area close to the head plate on the impact side is mandatory for reproducible test conditions and to avoid uncontrolled random fold initiation location.

The triggering alone however is not enough, the top impact 3mm head plate should also not be heavily welded over the whole crash box cross section, especially in the spot welded flange area, in order to avoid high crash box stiffness. A regular folding mode initiation is ensured by increasing the degrees of freedom between crash box upper edge and top head plate section.

The conclusions drawn here are valid for AHSS/UHSS in the tensile strength range 600-1200 MPa, the sample cross section being optimized for 1000 MPa tensile strength and 1.5 mm thickness. Due to the reduced bendability of UHSS in general a differentiation of AHSS/UHSS grades for crash application becomes a challenge. The introduced crash index quantification method allows with this regard a precise quantification of material damage on the crash box after testing.

This testing method however cannot be transferred directly to real size automotive components with other geometrical design constraints. Depending on design parameters (head plate or not, head plate fully constrained or only lightly welded, square, rectangular or trapezoid cross section, self-triggering tapered or straight profiles with constant cross section, laser/MIG welded flangeless geometries vs. spot welded flanges, no trigger vs. one or multiple triggers in a raw, trigger location in flange or wall areas, trigger manufacturing deep drawn, cold bended, cutouts, tailor heated etc…) some fully different crash test results can be obtained with the same material from catastrophic split & curling to nice regular folding, especially for UHSS with Rm ≥ 1000 MPa. Therefore crashworthiness should not be considered as an intrinsic material property but rather as a mixed interaction result between a given crash box geometry and a material. A quasistatic L-profile compression test offers an alternative testing procedure for material axial foldability assessment free of design parameters (no spot welds, no head plate) [25].

It should be questioned whether a thick top head plate is necessary at all, as seen for example in [15],[17],[18]. It may be useful for a defined load transfer, but it rather hinders crash folding initiation by additionally stiffening the top section of the crash box. At tensile strength ≥ 1000 MPa this stiffening effect definitely prevents the initiation of a regular axial folding pattern resulting in unstable buckling and curling effects, which is useless for a material crash behavior evaluation. This is a dilemma, since a head plate in a real component is necessary and usually strongly joined to the crash box and surrounding automotive body structure. This study aims therefore at harmonizing the axial crash testing in laboratory conditions for AHSS & UHSS material crash foldability and light weight potential ranking. A sample shape and crash procedure imitating a real axial crash component (trigger in the flange area but head plate lightly MAG welded only in the upper shelf wall section) is provided, still allowing a reliable differentiation of crashworthiness and lightweight potential of UHSS grades.

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