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Study on the impact behaviour of a new safety toe cap model made of ultra-high-strength steels

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ABSTRACT

In this study the crashworthy performance of an ultimate safety toe cap model made of high-strength steel was evaluated. The structural response to impact loading conditions under normative requirements was properly related to the potential of lightweight design for a significant thickness reduction. Two grades of fully martensitic steels were selected and numerical models modelling extensive plastic deformation and strain-rate dependence were performed. The mathematical description of the impact behaviour with the correlation of crashworthy properties was analysed and compared by applying two fundamental constitutive models: The Cowper–Symonds and Johnson–Cook constitutive equations. Experimental results of tensile testing at different strain rates and different directions of the sheet material were used to determine fundamental constitutive parameters for both steel alloys. The numerical simulation developed using an explicit dynamics software (ANSYS) was extensively compared to an experimental standard testing program of final prototypes. A local stiffening toe cap model with high energy absorption efficiency was also validated.

1. Introduction

Light-weight design has been a driving force for the research and application of light alloys, and in particular, high-strength steels. Since the remarkable project, ULSAB–AVC (ultra-light steel auto body–advanced vehicle concepts) [1] pointed out that crashworthiness and weight reduction are made compatible, therefore, the increase of fuel efficiency from replacing the conventional low strength steel by advanced high-strength steels (AHSS) and applying adequate forming techniques to reduce the number of parts and guarantee the strength optimization was more than just economic and environmental related issues. In addition, the repositioning of advanced steel alloys as a solution approach has been argued when final costs of raw materials, manufacturing value added, and mostly, crashworthy properties are demanding [1–3].

The toe cap represents the most normative integrant component in safety footwear with strict requirements in structural and crash deformation resistance [4]. Consequently, greater mechanical strength leads to undesirable technical features. The toe cap is the heaviest element contributing to approximately 35% of the average weight of standard High Performance Footwear and several problems are inevitably associated with health, fatigue in extended use and occupational injuries [5–7]. Thus, structural design and material selection of safety toe caps have been assumed a multidisciplinary conception trend, with division between metallic and polymeric composite models, as most of products on weight reduction research [7,8]. These non-metallic solutions are currently lighter. The recent and most relevant developments on polymeric and hybrid models combining reinforced polyester composites with glass fibre and other advanced compounds for safety toe cap components reported a substantial weight reduction, in excess of 30%, compared with standard steel toe caps made of high carbon steel alloys (widely combined with specific heat treatments) [9–14]. Nevertheless, the main disadvantage to the first ones is committed to several constraints due to the stabilization of deformation responses for higher compression and impact load conditions. Commonly, composite toe cap solutions require a larger volume, owing considerable thickness values to counterpoise higher rates of deformation and, in several ways, that affects the conception of fundamental integrant parts. In this context, an advanced metal solution has been investigating [15], in which the application of ultra-high-strength steels focuses a noteworthy role in absorbing impact energy.

The research program includes advanced steels with the extended martensitic phase to achieve tensile values up to 1400 MPa for a maximization process between strength properties and still adequate ductility to forming techniques. High-strength steels are also associated to strain-rate dependence and higher values of absorbed energy at high strain rates, when compared to other similar strength materials [2]. Although, it is undeniable that reliable design of structural impact requires an understanding of material properties, its strain-rate sensitivity is not always linear and consensual for all authors. Different impact load conditions for relevant and several applications, high-strength steel grades and dissimilar analysis for different strain rates have certainly influence. For instance, Huh et al. [16] and Peixinho et al. [17] compared dynamic tensile properties between high DP steels and equivalent TRIP steels at

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Nomenclature

h	area of cross section of Hopkinson bar
A_S	area of cross section of specimen
C	Johnson–Cook parameter of original equation
C_e	elastic wave speed
D	Cowper–Symonds parameter of original equation
E	Young's modulus
E_a	absorbed energy
E_a/w	absorbed energy per unit weight
E_8	absorbed energy during the first 8 mm crushing distance
E_8/w	absorbed energy per unit weight during the first 8 mm of crushing distance
L_0	initial length of thin-walled tubes
L_c	longitudinal length of specimen
L_s	effective gauge length of specimen
q	Cowper–Symonds exponent of original equation
P_m	mean crushing force
P_{max}	maximum crushing force
R^2	Coefficient of determination
$R_{p0.2}$	0.2% proof stress
t	time
T	temperature
UTS	ultimate tensile strength
v_0	linear speed of tensile test machine
v	impact velocity
ε'	strain rate
σ	stress
ε	strain
ν	coefficient of Poisson
ρ	material density
ε_y	strain at yield
ε_u	strain at UTS
AHSS	advanced high-strength steels
DP	dual phase
EN	European Standard
HSS	high-strength steels
UHSS	ultra-high-strength steels
ULSAB–AVC	ultra-light steel auto body–advanced vehicle concepts
ISO	International Organization for Standardization
Mart	martensitic
TRIP	transformation induced plasticity

intermediate strain rates from quasi-static to 200 s^{-1}, and it was found an increase of the flow stress with higher strain rates and slightly differences between material models. Yu et al. [18] also concluded that DP600 is strain-rate sensitive for both yield and ultimate tensile strength between higher ranging analysis of 10^{-4} to 10^{3} s^{-1}. Abedraboo et al. [19] studied the crash response of high-strength steels and concluded that DP600 has greater strain-rate dependence than DP780. Yoon et al. [20] analysed a Mart1200 model with minor strain-rate response but with a significant absorbing energy capacity for a comparative crashworthiness assessment. Tarigopula et al. [21] observed in their heavy axial crushing of thin-walled-high-strength steel sections that strain-rate effects are only dominant compared with inertia effects for low-velocity axial impact. Boyce and Dilmore [22] remarked limited data available in the literature regarding deformation behaviour at intermediate strain rates in the range of 10–500 s^{-1} due to testing difficulties in the "sub-Hopkinson" strain-rate regime. Although these authors have found that four HSS steels have experienced modest levels of strain-rate sensitivity under 200 s^{-1}, notwithstanding, this regime was considered relevant for many applications and typically quasi-static properties have been misapplied.

In this paper, two ultra-high-strength and fully martensitic steel grades were selected from the research project and one of the main objectives of the present study was to assess the influence of intermediate strain rates on crashworthy properties for an axial impact velocity of around 4 ms^{-1}. Experimental results of tensile testing of the selected steel grades were used to determine constitutive parameters and thus to simulate the impact behaviour of toe cap prototypes. Efficient constitutive models with simple constitutive equations are generally capable to describe numerical and analytically structural impact problems, such as the Cowper–Symonds equation [23]. The foremost limitation of a simplified constitutive model is to cover a full behavioural prediction at higher strain-rate ranges and following thermal effects may also be considered at that level. Modified constitutive equations are therefore proposed to crash conditions with larger impact strain rates or other complex dynamic events [24]. Another phenomenological model highly useful and successfully applied is the Johnson–Cook constitutive equation [25]. In this context, these two constitutive equations in the original form were here selected and their responses are compared in this study. Furthermore, different constitutive parameters are also obtained when considering the ultimate tensile strength (UTS) or the proof stress as reference stresses to fitting the Cowper–Symonds equation [26]. Different numerical simulations are thus presented in this study and, additionally, different directions of the experimental tensile tests were also considered due to anisotropic evidence in the two martensitic specimens.

The numerical models were duly compared with experimental results of the normative impact testing for an ultimate geometric toe cap model. Hence, the numerical predictions can be validated and conclusive evaluation of constitutive modelling can be made. Additionally, the improvement analysis of reformulated contact conditions was performed in order to accurate numerical deformation modes and experimental results of other prototype models were also included to enhance the crashworthy analysis.

2. Material properties

Toe cap prototypes made of cold reduced martensitic steels were selected in this study. Two ultra-high-strength steels, Mart1200 and 1400 using special heat treatment in a continuous annealing line and presenting high strength for adequate formability in this specific case were produced and delivered by SSAB (Swedish Steel Ltd.). The nominal chemical composition of both materials is presented in Table 1. Nominal mechanical properties for different directions of sheet material: longitudinal and transverse to the rolling direction were determined due to evidence of anisotropic responses.

Experimental results of quasi-static and intermediate strain-rate tensile testing were conducted by the SSAB Knowledge Service Centre and laboratory facilities in Borlänge, Sweden. Flat specimens of 1.50 mm of thickness, longitudinal length of 105 mm for a total length of 250 mm and an extensometer gauge length of 80 mm were tested at strain rates between 10^{-4} and 2.5×10^{-4} s^{-1}, respectively for both materials at angles of 0° and 90°. These quasi-static tests were carried out using servo-hydraulic testing equipment according to EN6892 and EN10113 standards. Fig. 1 presents engineering stress–strain curves obtained for Mart1200 and 1400 at different directions.

Dynamic testing of all material specimens with smaller gauge length (approx. 60 mm) was conducted using a displacement controlled servo-

Table 1
Nominal chemical composition of martensitic steels in wt.% [27,28].

Steel grade	C	Si	Mn	P	S	Al	Nb + Ti
Mart1200	0.14	0.40	2.0	0.02	0.010	0.015	0.10
Mart1400	0.20	0.40	1.60	0.02	0.010	0.015	0.10