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Enhanced Nonlinear Material Modelling for the Analysis and Qualification of Rollover Protective Structures (ROPS)

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Abstract

Finite element (FE) simulation of rollover protective structures (ROPS) is an important aspect in its design, as it provides a means of structural integrity qualification prior to the required destructive testing. A good understanding of the ROPS behaviour under simulated loading offers engineering practitioners the opportunity to optimise the design. The testing conditions, outlined in the applicable standards, result in ROPS plastic deformation, associated with material hardening of various areas of the structure. The accurate description of the material behaviour is important for the FE simulation of structural response. This research examines some of the hardening models commonly used in ROPS simulations, which are available in most FE commercial software, including linear / multilinear isotropic and kinematic hardening and nonlinear kinematic hardening. The numerical performance of the plasticity models in capturing the material behaviour has been compared against the experimental data of commonly used ROPS material. The analysis has revealed the potential benefits and drawbacks of the various models. Moreover, a damage-induced softening model has been implemented at the structure joints in conjunction with the nonlinear hardening models. Enhanced computational results were obtained through this modelling variation, highlighting the importance of material modelling at the primary structure and the joints of ROPS.

Keywords

Rollover protective structures (ROPS), plasticity, isotropic, kinematic, modelling, finite element analysis, nonlinear analysis, welds, strain softening.

Introduction

Rollover protective structures (ROPS) are used to provide safety to vehicle drivers and equipment operators of heavy vehicles by containing damage (e.g. rupture, plastic deformation) that may occur from an accidental event (e.g. Figure 1). Substantial research efforts have been undertaken to develop experimental and computational qualification techniques capable of replicating the response of ROPS to crash and rollover scenarios prescribed by relevant standards, such as SAE J2194[1], OSHA 1928.52[2] and ISO 3471:2008[3]. As an example, ISO 3471:2008, which is the most commonly used industry standard worldwide, requires physical testing of the ROPS design, which involves a destructive full scale loading test. During this test the structure is subjected to three consecutive loading cases: lateral loading and unloading, vertical loading and unloading and longitudinal loading and unloading. The loads in each of the three cases are applied at a slow deflection rate of 5 mm/s. This ISO standard specifies the force and energy requirements related to the mass and type of machinery, which must be met during testing. The structure has to satisfy these requirements, while the severity of deformation must be sustained to a minimum level, preventing intrusion of the structure into the space allocated for the operator, referred to as the Dynamic Limiting Volume (DLV) (an orthogonal approximation of a large male operator wearing protective clothing).

Figure 1. Typical ROPS structure (yellow dashed outline) of a modern tractor (photo from: Solitude [CC BY-SA 2.0 (http://creativecommons.org/licenses/by-sa/2.0)], via Wikimedia Commons).

Due to the large forces applied to a ROPS during the destructive testing, the ROPS responds nonlinearly as the material yields and exhibits inelastic behaviour. FE modelling of the ROPS behaviour aims to minimise the need for prototypes, which increase the cost and time for development and certification. As identified in literature and presented in the sequel, existing modelling practice relies on linear approximations of the non-linear inelastic behaviour of the materials used in ROPS structural members. To the authors' best knowledge, no previously published research in ROPS engineering has utilised or investigated advanced non-linear material modelling. Instead, linear/bilinear[4-

[10] and multi-linear[11-14] material hardening or even the simplistic Ramberg Osgood curve fitting equation[15] have been extensively employed for various cases of ROPS subjected to different loading scenarios. This commonly adopted practice is considered by most researchers as being sufficient to simulate effectively the material behaviour observed during a simple loading/unloading case. Nevertheless, the ROPS loading sequence during standard tests may lead to material deforming plastically during reverse loading and most profoundly to the appearance of the Bauschinger effect[16]. The Bauschinger effect can be simply described as the decrease of the yield stress in compression (σ_Y') of a component which had previously undergone plastic deformation in tension (initial yield stress σ_Y), as shown in Figure 2.

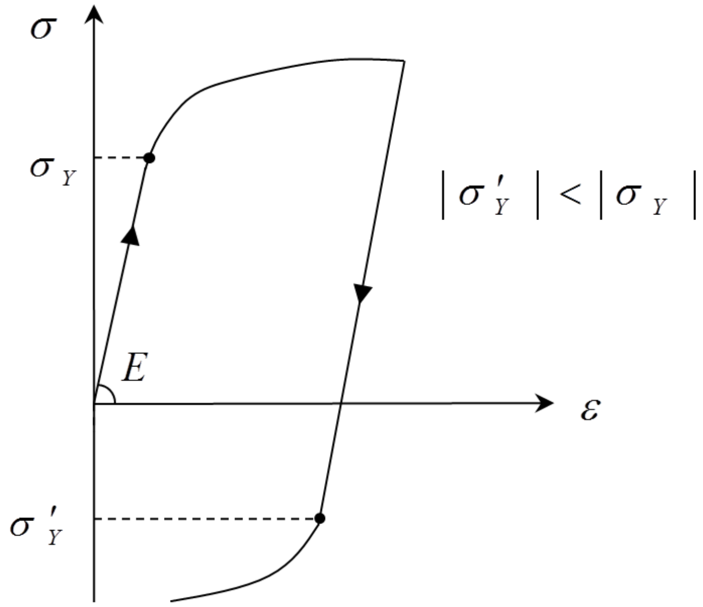


Figure 2. Schematic representation of the Bauschinger effect, where σ_Y is the yield stress upon initial loading and σ'_Y is the yield stress upon reverse loading

The linear approximation approach is not capable of accommodating this complex material behaviour, which in turn leads to non-realistic simulation of material behaviour and structural response. Moreover, it is noted that the impact of ineffective material modelling in simulating structural behaviour is amplified by other modelling challenges, such as the complex response of welded joints. This article presents and compares different approaches to material modelling, available in most FE analysis software, which can be used for simulating the structural behaviour of ROPS. Comparing these modelling approaches highlights the shortfalls and advantages, thus, providing a better understanding of these material models. Implementing such modelling solutions can benefit the overall accuracy of simulations. The primary objective of this research is to inform the research community as well as engineering practitioners working on the qualification of ROPS structures. This is performed by highlighting the importance of considering nonlinear kinematic hardening models in the material definition of FE models, rather than linear and multilinear models which are commonly applied in ROPS simulations.

Material plasticity modeling

The rate-independent mathematical theory of plasticity is able to describe sufficiently the ROPS material behaviour under a structural qualification testing campaign, since low strain/stress rates are applied (5 mm/s deflection). Also, temperature independency is assumed, since the tests are conducted at room temperature. The underlying theoretical background and formulation is not presented in detail as the primary focus of this article is to offer an insight into specific material models incorporated into commercial FE software packages (e.g. ABAQUS, ANSYS). As an example, Table 1 presents various kinematic hardening models which are incorporated in such programs. The user can select any of these models via the software interface, while the material selection methodology is explained in the accompanying user manual / handbook of its software.

Kinematic hardening Model	**FE Software**		
	Ansys 13	**Abaqus**	**MSC.Marc**
Bilinear	Prager	Ziegler	Ziegler
Multilinear	Besseling	Unavailable	Unavailable
Non-linear AF	Available	Available	Available
Non-linear MAF	Available	Available	Unavailable

Table 1. Examples of kinematic hardening plasticity models incorporated in commercial FE software packages.

For these reasons, these simple plasticity (kinematic hardening) models are very popular among engineering practitioners, despite the limited accuracy they offer as presented in the sequel. This section describes briefly the two primary types of hardening. It also presents the main features and formulation of various material hardening models.

Hardening Models

The two most commonly used models of hardening in metal plasticity are the isotropic and kinematic hardening. These are used to describe in a simple manner the changes of the yield surface during plastic loading. The yield surface, expressed mathematically by the yield function (F) in the generalised stress space (S), represents the locus of points defining the boundary between elastic ($F < 0$) and inelastic material behaviour ($F \geq 0$). Stresses applied on a material beyond this boundary impose plastic behaviour which, for most metals, leads to the increase of the yield stress (hardening). The yield surface may undergo different kinds of changes within the stress space during the course of plastic loading (applied stress that exceeds yield stress), such as expansion, translation, rotation, distortion, etc. These changes for most engineering applications can be approximated through isotropic (expansion of yield surface), kinematic (translation of yield surface) or combined isotropic-kinematic hardening. In particular, isotropic hardening imposes a uniform expansion to the yield surface, expressed through the increase of the (scalar) value of the yield stress k from k_1 to k_2 where $k_1 < k_2$ (Figure 3a).

On the other hand, kinematic hardening induces a movement of the yield surface, dictated by the backstress a (tensor) which repositions the centre of the yield surface (Figure 3b). In this context, material hardening can be described, in mathematical terms, by employing different rules for the evolution of k (isotropic hardening) and a (kinematic hardening) or both (mixed hardening). These evolution rules are referred in the sequel as kinematic, isotropic or mixed hardening models.

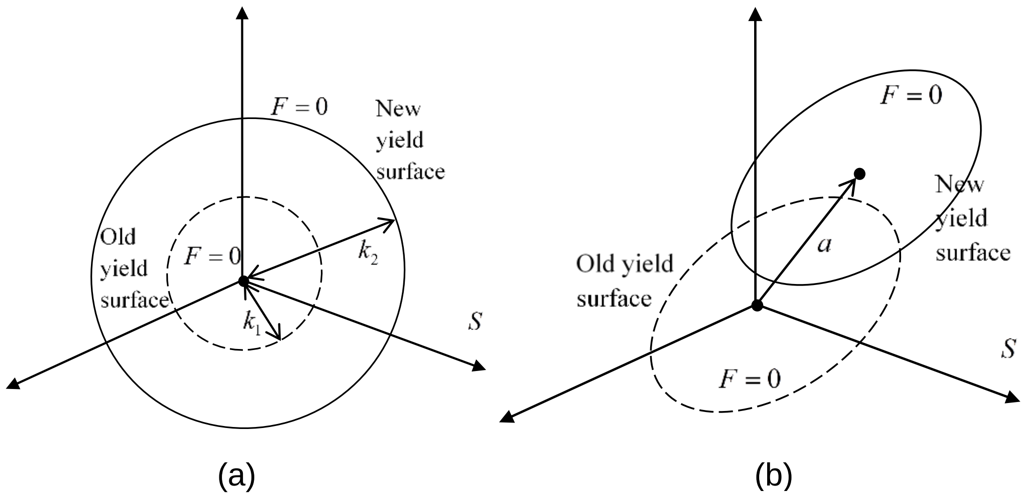


Figure 3. Schematic representation of (a) isotropic hardening and (b) kinematic hardening in the generalised stress space (with S defined as the stress tensor in multiaxial stress state).

In the uniaxial stress space (where the stress tensor S is being reduced to a single uniaxial stress σ), the yield function can be described by the following mathematical expression:

$$F = f(\sigma - a) - k^2 = 0 \qquad (1)$$

where f is the yield criterion, which is a function of stress σ, the backstress a, and the yield stress k. For the case of the von Mises yield criterion relation (Equation 1) takes the following form:

$$F = \frac{3}{2}(\sigma - a)^2 - k^2 = 0 \qquad (2)$$

Through Equation (1) [or Equation (2) for the case of von Mises], one can obtain:

- Isotropic hardening by having $k = k(\varepsilon^p)$ and $a = 0$
- Kinematic hardening by having $k = k_0$ and $a = a(\varepsilon^p)$ where k_0 the virgin material (initial) yield stress ($\sigma_Y^{initial}$)
- Mixed (isotropic and kinematic) hardening by having $k = k(\varepsilon^p)$ and $a = a(\varepsilon^p)$

Isotropic hardening models.

The most commonly applied isotropic models, in ROPS' engineering published research, used to describe the evolution of k, are the linear and multilinear hardening types. Both of these evolution laws are developed from a linear relationship, which can be defined for the case of uniaxial loading as follows:

$$dk = hd\varepsilon^{p} \qquad (3)$$

where h is the hardening parameter (constant) and is defined with reference to the gradient (slope) of the plastic flow curve. For linear hardening, a single value of h is used to approximate the gradient of the flow curve, while multilinear hardening requires the definition of a number of segments each with a corresponding gradient. An illustration - comparison of the two models characteristics, against previously published experimental data, is provided graphically in Figure 4.

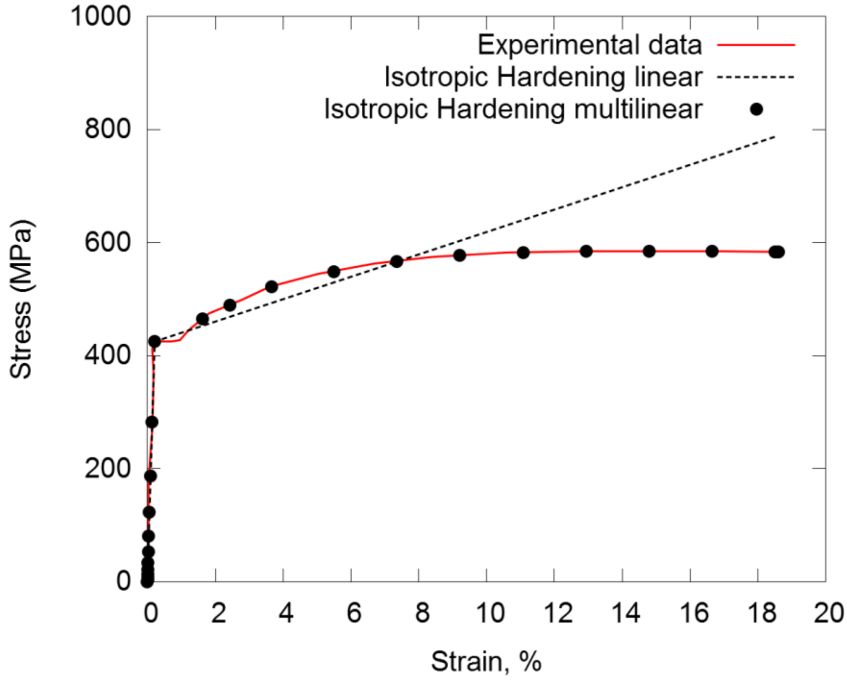


Figure 4. A comparison of the linear and multilinear isotropic hardening models for the case of monotonic loading (experimental data obtained from Shi, Wang [17])

Figure 4 provides also an indication of the extent of the difference between the linear and multilinear models. Vital material monotonic behaviour characteristics are captured more effectively by the multilinear model. However, the effectiveness depends on the number of data points defining the monotonic curve, as shown in Figure 5. Figure 5 demonstrates how the non-linear behaviour of the material is better represented by the graph (b) which is defined with five data points, compared to graph (a) which is only defined by three points.

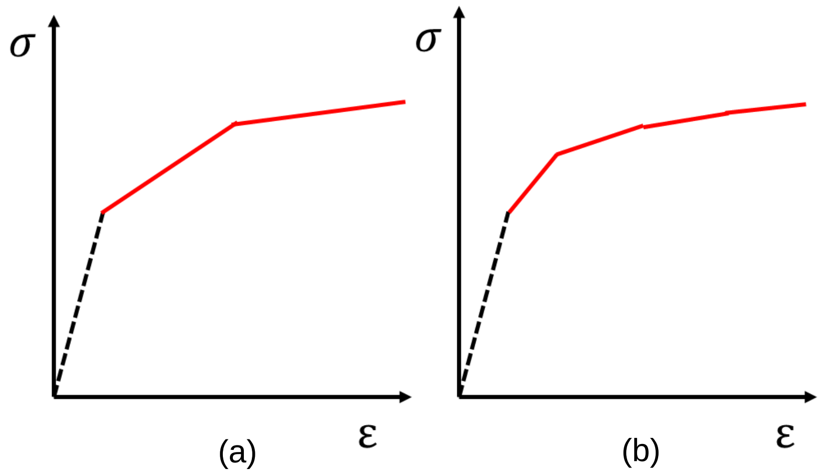


Figure 5. Multilinear data point definition comparison: (a) two points, as opposed to (b) five points.

Kinematic hardening models.

Linear kinematic hardening is a hardening model commonly applied in ROPS simulations. The Prager[18] and Ziegler[19] hardening laws define the evolution of backstress a. The two laws are equivalent when using the von Mises yield criterion. However, this is not the case if Tresca or any other yield criterion is used. This is attributed to the different definitions of the yield surface translation direction.

The Prager backstress definition for the uniaxial case is defined as follows:

$$da = \frac{2}{3} c d\varepsilon^{p} \tag{4}$$

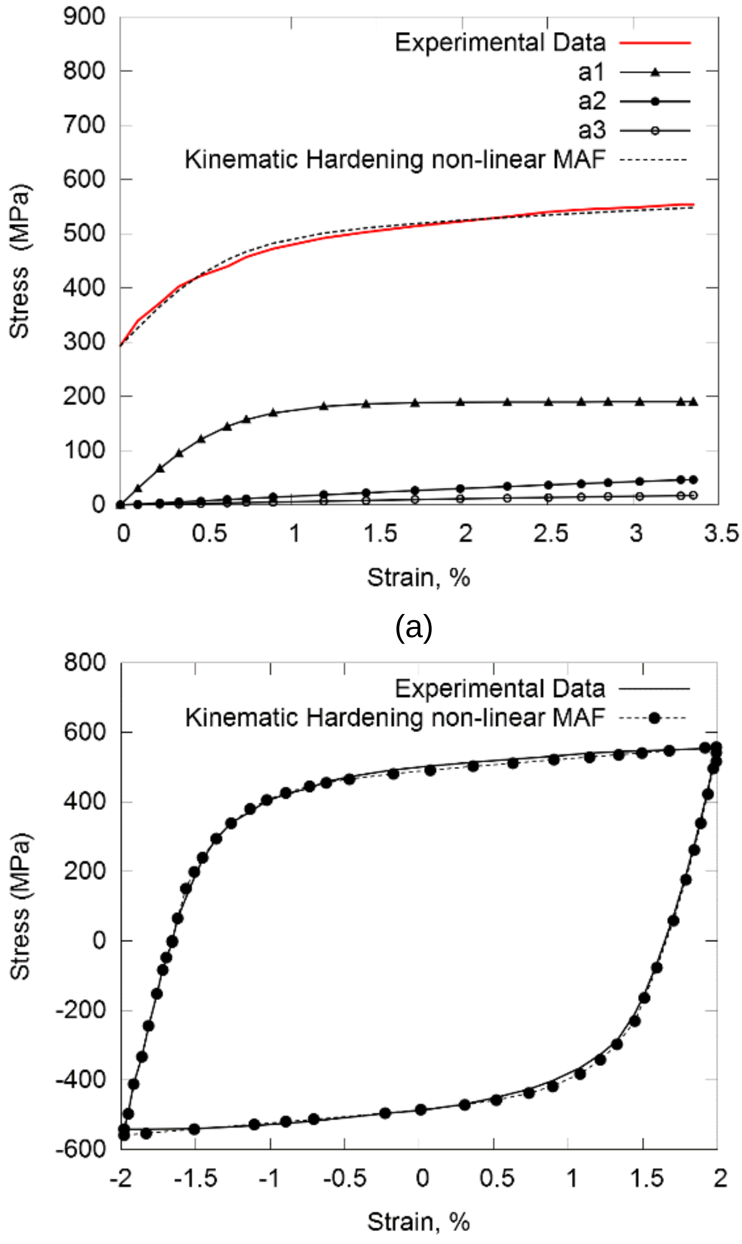
where c is the kinematic hardening modulus. In the case of linear hardening, the value of c is the gradient of the plastic flow curve.

A model which has not been applied in published research to ROPS analysis is the Armstrong–Frederick (AF) hardening model[20]. The AF model is an extension of the Prager hardening rule, as an extra term is added (dynamic recovery term). As the backstress evolves beyond the material initial yield stress, the dynamic recovery term decelerates its growth rate, imposing that way a non-linear response to the hardening rule. The backstress for uniaxial loading can be defined by the following relation:

$$da = \frac{2}{3} c d\varepsilon^{p} - \gamma a d\varepsilon^{p} \qquad (5)$$

where γ regulates the stress saturation rate and the ratio of $\frac{c}{\gamma}$ defines the saturation stress level.

Chaboche, Dang-Van [21] developed the AF model further in order to provide a more robust model allowing for better experimental data fitting, especially at higher strain levels. Chaboche, Dang-Van [21] noted that the success of the AF model was limited by the use of only one exponential term. A model containing the superposition of three (or more) AF backstresses was proposed, which is also known as the Multicomponent AF (MAF) model. MAF model relies on combined operation of different backstresses, with each of the backstresses capturing a different feature of the hysteresis curve. For example, the first backstress captures the initial modulus at the onset of yielding; the second backstress captures the nonlinear transition between the onset of yielding and the linear segment of the curve and the third backstress captures the linear curve segment which takes place at higher strain levels. Figure 6a provides an example of each of the backstresses' contributions, while Figure 6b presents the combined effect.



(b)

Figure 6. (a) Definition of the three backstresses used in the MAF model (experimental data obtained from Shi, Wang [17]). (b) The combination of the

backstresses provide for a good definition of the material hysteresis curve (experimental data obtained from Shi, Wang [17]).

Various modifications of the MAF model have been developed by researchers over the past 30 years (e.g. Chaboche[22], Ohno and Wang[23, 24], Dafalias, Kourousis[25], Feigenbaum, Dugdale [26], etc). The modifications aimed to improve simulation of complex phenomena observed under uniaxial and multiaxial cyclic loading cases. Utilising these models for ROPS simulation is too cumbersome for engineering practitioners, due to their high level of sophistication, while accuracy is not expected to improve significantly for the case of ROPS structures' loading histories (practically limited to one and a half cycle: loading, unloading and reloading).

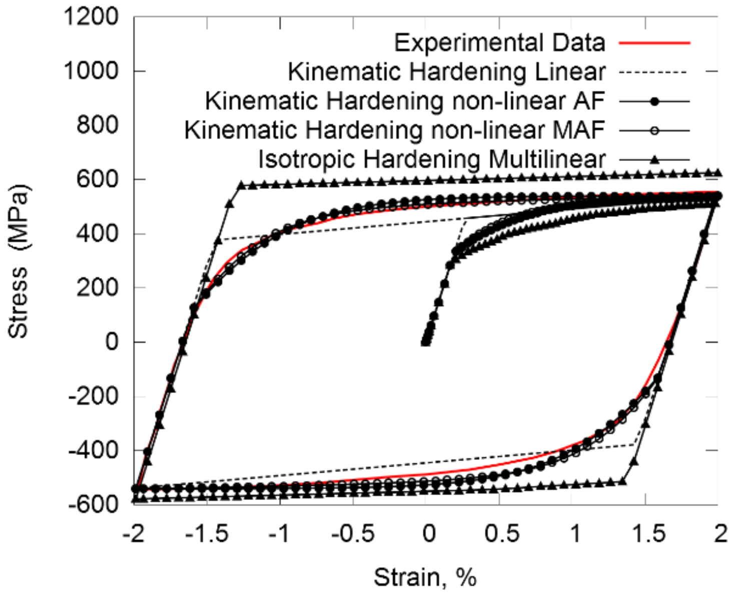
Comparison of material models

A comparison is performed between isotropic and kinematic hardening rules, presented in the previous section. In particular, isotropic hardening rule is compared to the linear, non-linear AF and non-linear MAF kinematic hardening rules. The outcome is validated against published experimental data[17]. Figure 7a and Figure 7b present simulations obtained for two types of strain-controlled cyclic loading of Q345B grade steel, a structural steel alloy commonly used in ROPS. Figure 7a shows the simulation results for a symmetric loading, while Figure 7b is an asymmetric loading. The presented material models are compared in order to give a better understanding of the ability of each model to capture behaviour of the material. The material model parameters used are shown in Table 2 and were calculated with reference to the loading branch of a stabilised symmetric strain-controlled hysteresis loop of Q345B experimental data. The parameters for the nonlinear kinematic hardening models were obtained using the method described in the previous section, used to develop Figure 6a and Figure 6b. The linear kinematic hardening parameters were calculated to also fit the stabilised loading branch, and was subsequently adjusted to ensure the stabilised hysteresis loop was captured well.

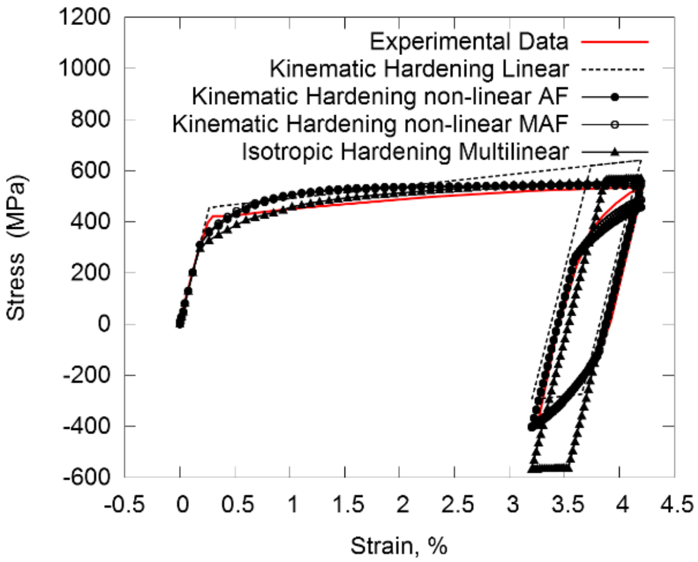
Similarly, multilinear isotropic hardening parameters were also obtained from the stabilised loading branch of the symmetric strain-controlled experimental Steel Q345B data, by defining segments along the branch as defined in Figure 8.

The parameters for the non-linear hardening models, namely AF and MAF were obtained through implementing the methodology (procedures) described in the original papers of Armstrong and Frederick[20] (AF model) and Chaboche et al[21] (MAF model). For the case of the linear hardening models (isotropic multilinear and kinematic linear) a simple curve fitting process was utilised. For all cases (both linear and non-linear hardening) a manual fine tuning of the parameters was performed, to allow for improvements of the simulated results.

As it can be seen from the results, the nonlinear material models can capture more accurately the complexity in the material behaviour, as opposed to the simple linear hardening models. The improvement in the simulation of a simple asymmetric loading case such as that in Figure 7b gives an indication of the potential improvement to ROPS simulations with the application of a nonlinear kinematic hardening model rather than the linear models which have previously been applied.



(a)



(b)

Figure 7. Comparison of simulations obtained for various plasticity models for the case of (a) 2.0% symmetric strain-controlled cyclic loading and (b)

asymmetric strain-controlled cyclic loading (4.2% maximum strain, 3.2% minimum strain) (experimental data obtained from Shi, Wang [17]).

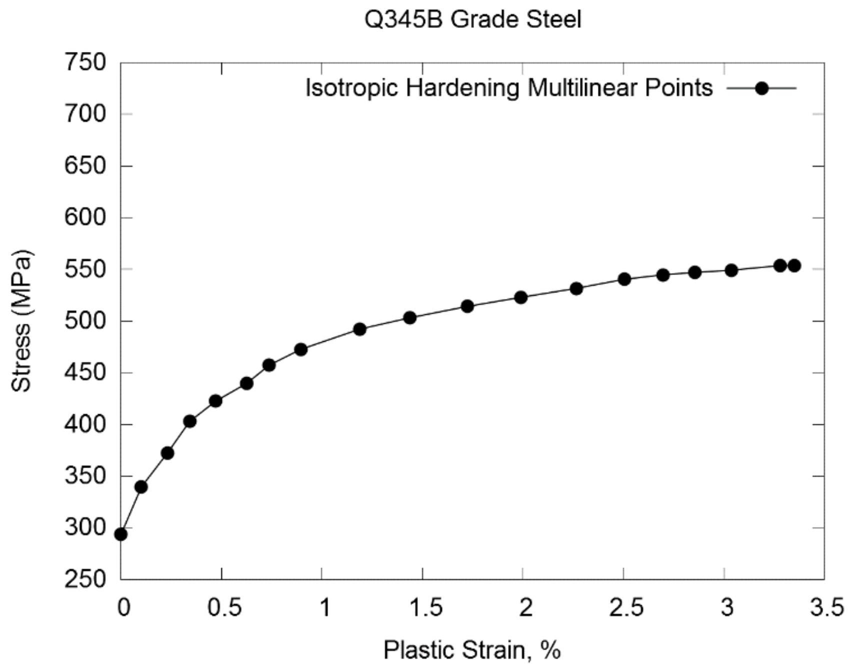


Figure 8. Multilinear isotropic hardening material parameter determination from steel Q345B data (experimental data obtained from Shi, Wang [17])

Hardening Model		**Backstress**					
		a_1		a_2		a_3	
		C_1**(MPa)**	γ_1	C_2**(MPa)**	γ_2	C_3**(MPa)**	γ_3
Kinematic	**Linear**	4,818	0	-	-	-	-
	Non-linear AF	52,500	250	-	-	-	-
	Non-linear MAF	54,600	390	9,200	230	2,000	40
Isotropic	**Multilinear**	Refer to Figure 8 for data point definition.					

Table 2. Material parameters of the various plasticity models in comparison.

ROPS Finite element analysis

To demonstrate the importance of appropriate selection of material hardening models, the multilinear isotropic hardening model and the MAF model were compared using finite element analysis (FEA) software (Dassault Systemes Abaqus FEA). A simple ROPS finite element model (FEM) (Figure 9) was developed based on the two-post ROPS utilised in the research conducted by Clark[27, 28] in static and dynamic testing.

Model setup

The model was meshed using linear shell elements with reduced integration (S4R)[29] in order to prevent any issues with shear locking which could lead to inaccurate deflection results. An initial mesh size of 10 mm was selected for the structure, with a finer mesh of 5mm at the joints to allow for the definition of strain softening elements, used to simulate the potential formation of weld cracks. The joints where these elements were applied are highlighted in Figure 9, defined as the joints between the horizontal and vertical beams. The significance of weld cracking has been highlighted by a number of ROPS researchers[6, 7, 9]. Therefore, it was deemed appropriate for the model to account for the potential occurrence of this failure mechanism by introducing a means of reducing the stiffness at these locations upon reaching a specified stress level. Improving joint stiffness was considered by Park and Yoo [30] who implemented nonlinear spring elements at the joining are of the beam elements to improve buckling simulation and reduce the over stiff response in the simulation of bus rollover.

The analysis was conducted using Abaqus Explicit to allow for the application of strain softening elements. The explicit method can more effectively simulate the large deformations formed in the ROPS test, however, due to the slow deflection rate required by the ISO standards, the simulations are time consuming, a dilemma highlighted by Cesa and Oliveira [14] when selecting the most appropriate method (explicit or implicit) to apply in ROPS simulations. The application of the explicit method to quasi-static rollover simulations such as this, has been effectively applied by Liang and Le [31], in the vertical loading of a bus (force applied to the vehicle roof). Explicit LS-DYNA solver was used to achieve very good experimental and simulation result correlations.

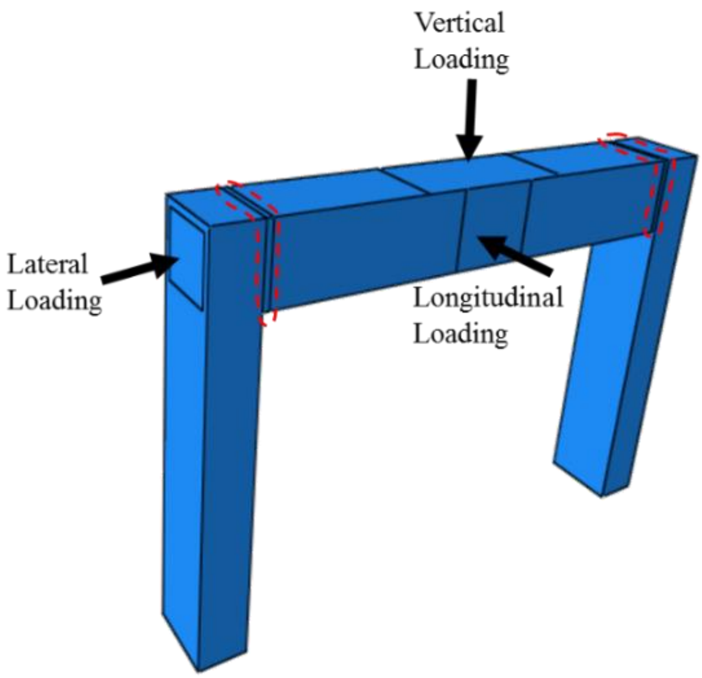


Figure 9. ROPS geometry (Abaqus model) with defined load application and strain softening element definition (indicated with red dashed lines).

Loading Sequence

Figure 9 shows the applied load areas on the ROPS structure, for the three testing cases, as per sequence outlined in the corresponding ISO standard[3]:

- Lateral loading and unloading;
- Vertical loading and unloading;
- Longitudinal loading and unloading.

In order to avoid the occurrence of excessive deformation at the points of load application, Clark[27, 28] suggested the application of a slightly larger shell thickness compared to the rest of the structure. In addition, elastic material definition was used at these regions. Both of these model attributes were adopted for this simulation, where the force application region was increased to a shell thickness of 10 mm compared to the rest of the structure which had a thickness of 5.0 mm.

Material modeling

The ROPS structure material elected for the FE analysis was 350 grade steel due to the availability of published test results. Inelastic material behaviour was modelled with both the multilinear isotropic hardening rule, which is commonly used for ROPS simulations, and the MAF kinematic hardening rule. The data points for the isotropic hardening model (Figure 10) were obtained from uniaxial tensile tests conducted by Clark[27, 28] on 350 grade steel specimens. Since no cyclic data was available for this alloy, the parameters for the MAF model were approximated from the uniaxial test data (presented in Table 3).

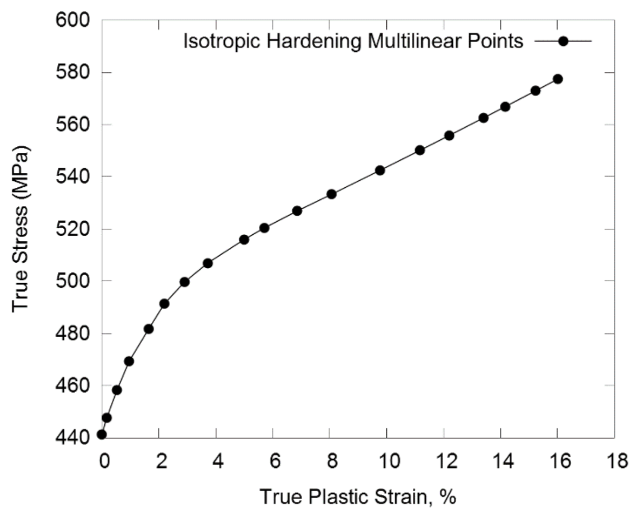


Figure 10. Multilinear Isotropic hardening modelling of 350 grade steel (experimental data obtained from Clark[27, 28])

Hardening Model	**Backstress**					
	a_1		a_2		a_3	
	C_1**(MPa)**	γ_1	C_2**(MPa)**	γ_2	C_3**(MPa)**	γ_3
Kinematic Hardening non-linear MAF	1,100	40	2,100	85	10	0
Isotropic Hardening Multilinear	Refer to Figure 10 for data point definition.					

Table 3. MAF material parameters used in the Abaqus finite element (FE) model.

Emphasis was placed on modelling the joints due to the predominant role they have on the overall inelastic behaviour of the ROPS structure. This was considered important in view of comparing the simple isotropic model not only to the MAF kinematic hardening model but to a variant incorporating some features enabling more realistic representation of the structure response. In this regard, the material at the joints (within a vicinity of 10 mm) was modelled to include damage. This choice was based on the assumption that damage would induce a strain softening behaviour in the material (as observed in actual ROPS testing). In particular, damage is assumed to initiate upon yielding of the base material (at 440 MPa). Figure 11 provides a schematic representation of the strain softening definition. This definition attempts to emulate the formation of a crack. The softening fracture strain is defined at approximately 10%, as approximated from tests conducted by Svard[13]. Damage (D) can be defined as the degradation of the mechanical strength of the structure caused by monotonic stress (as with the case examined) or cyclic stress. Once the damage point is reached (D at start equals to zero, or else D=0), the stress starts to decrease. Eventually, stiffness is further reduced in any consequent loading step, since it then follows a new path prescribed by the evolving damage (D) accumulation.

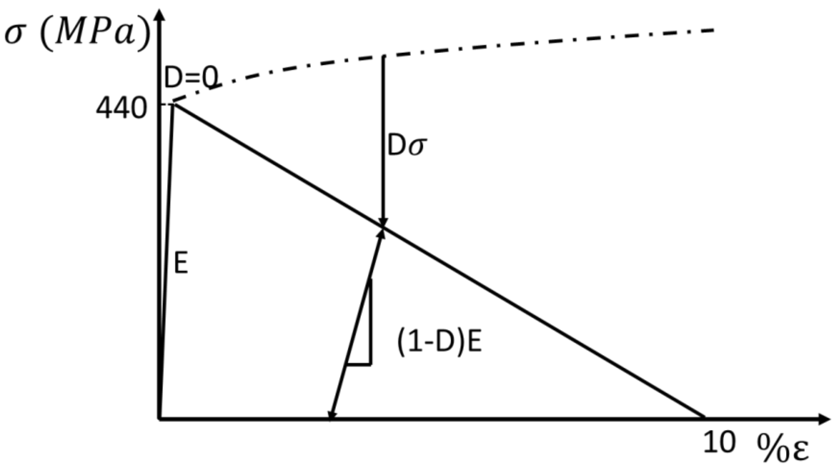


Figure 11. Schematic representation of the strain softening definition based on damage (D) accumulation, where E refers to the material Elasticity Modulus.

Therefore, three different material models were adopted for conducting ROPS simulations in Abaqus: multilinear isotropic hardening, MAF kinematic hardening and MAF kinematic hardening with strain softening at the joints.

Simulation results

The lateral, vertical and longitudinal loading cases were simulated in Abaqus for the three different models presented in the previous section. As discussed in the sequel, the comparison highlights the importance of correct selection of hardening models, particularly in conjunction with strain softening elements.

The lateral loading case simulations (Figure 12a) revealed no real difference in the accuracy achieved for the three hardening models (isotropic, MAF kinematic and MAF kinematic with softening). The experimental results were replicated well by all models. This was an expected outcome, since issues associated with the Bauschinger effect would not arise until further load application (re-loading/unloading).

For the vertical loading case, the load application is performed consecutively. Effectively, some deflection in the vertical direction occurs due to the deformation enforced by the lateral load case (which was applied first). The simulation results achieved, shown in Figure 12b, using a multilinear isotropic hardening and kinematic hardening model with strain softening are very similar.

It is observed that the multilinear isotropic hardening simulation results without strain hardening does not follow the experimental trend. However, the strain softening elements (MAF kinematic hardening model with softening) mitigated the discrepancies reported by Clark[27, 28] (over-stiff simulation results). The improved simulation accuracy is attributed to element stiffness degradation, an effect of the strain softening at the joint elements.

The results obtained from the longitudinal loading case (Figure 12c) demonstrated significant differences between the hardening models. Although the overall results were still quite stiff. For all models, a lower stiffness obtained from adopting the MAF model with strain softening. The isotropic hardening model, due its inability to capture the Bauschinger effect, has produced a stiffer (less accurate) behaviour.

Examining the overall performance of the models (in all three loading cases) provides an insight into the challenges that have to be met for accurate ROPS simulation. The major difficulty in replicating the deflection behaviour of the structure is being able to accurately simulate the structural deformation occurring during each load case. The first load case (lateral case) is the simplest case to simulate since it is undeformed, consequently, the deflection behaviour is not influenced by previous load cases.

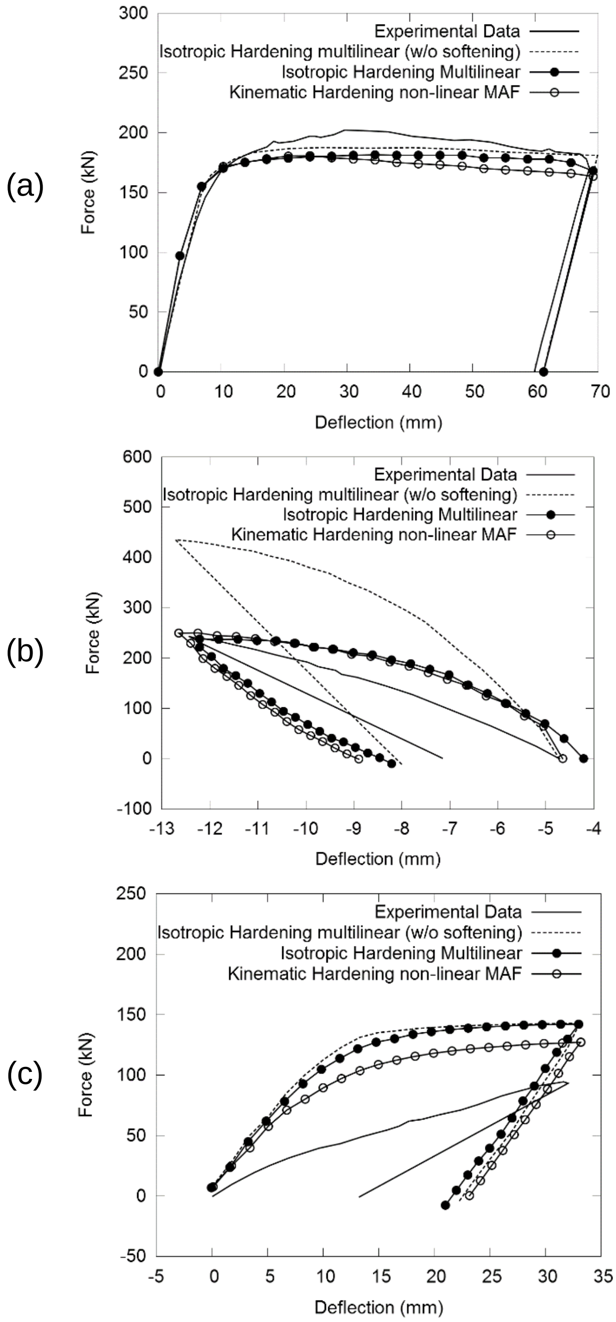


Figure 12. (a) Lateral, (b) Vertical and (c) Longitudinal loading comparison (experimental data obtained from Clark[27, 28])

Discussion and conclusion

The selection of the most appropriate hardening model when performing FE analysis is important in improving the accuracy of simulations and consequently enhancing design and qualification capabilities. The multiaxial cyclic behaviour exhibited in structures under mixed loading cases needs to be accounted for through the selection of suitable hardening models. As described, cyclic behaviour cannot be modelled accurately by adopting simple isotropic hardening models, as these are not capable of capturing the Bauschinger effect. This deficiency of the isotropic hardening models leads to a potential over-prediction of stresses in the direction opposing plastic flow (unloading/reverse loading in the plastic region).

Kinematic hardening models can be broadly classified into linear and non-linear hardening (based on the type of hardening rule they deploy). Each class of models accounts for the Bauschinger effect. However, comparison shows advantage of the nonlinear (AF, MAF) hardening models over the linear (Prager) models.

Results obtained from the simulation of a simple two-post ROPS highlighted the importance of using kinematic hardening models. The isotropic model under-predicted the deflection the structure experienced during the longitudinal load case. Another important outcome of this investigation is the improved accuracy due to incorporating strain softening elements. In particular, the results demonstrate how the stiffness of the model is reduced due to the inclusion of strain softening elements, thus providing a more accurate simulation. The strain softening elements, in conjunction with non-linear kinematic hardening models have demonstrated an enhancement capability in FE modelling of ROPS structures.

This research study has attempted to demonstrate that there are various ways to improve the FE model in order to achieve better simulation results. This includes the use of strain softening elements to incorporate damage effects into the model, but also improved plasticity modelling with the application of kinematic hardening models in order to improve the prediction of stresses in consecutive load cases. Therefore, the aim is to reduce the accumulation of errors arising from the consecutive application of different loads (under various loading cases). Further work is in currently in progress, focusing on refining the allocation of the strain softening. This is expected to further improve the simulation accuracy.

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