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EDITED BY:
MUHAMAD ALIAS MD JEDI
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ORGANISED BY:
COMPUTATIONAL AND EXPERIMENTAL MECHANICS RESEARCH GROUP (CEM), UKM
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NONLINEAR MATERIAL PROPERTIES WITH PARAMETER UNCERTAINTY FOR STRUCTURAL ANALYSIS

Bon, Z. H., Kamil, S. (USK), Suffian, M. S. Z. M. (UNIMAS) & Ihsan, A. K. A. M.
Department of Mechanical and Manufacturing Engineering,
Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia
Tel: +601155059626 Email: bonzhihao@gmail.com

ABSTRACT

Finite Element Analysis (FEA) plays a pivotal role in understanding and predicting structural behaviour, particularly when dealing with material nonlinearities and complex stress-strain relationships. This study aims to develop a computational model for bar elements, incorporating uncertain nonlinear material properties using Fuzzy Random Variables (FRV) within Excel Visual Basic Applications (VBA). Focusing on one-dimensional bar element modelling, we utilise the kinematic bilinear model for the stress-strain curve of Wire Arc Additive Manufacturing High Strength Steel (WAAM HSS). The results demonstrate that FRV provides a more precise depiction of material behaviour in the nonlinear domain, effectively accounting for uncertainties in material properties and nonlinear stress-strain relationships. The findings reveal a nonlinear stress-strain correlation with yield deviations surpassing the yield strength at random intervals. Analysing failure percentage trends with increasing membership numbers via the FRV approach shows consistency and convergence of the findings, in contrast to the randomness approach, which lacks specific trends. Consequently, FRV holds promise for enhancing structural risk assessment, thereby improving material safety, efficiency and longevity.

Keywords: Structural Behaviour, Material Nonlinearities, Uncertainties, Stress-Strain Relationships, Risk Assessment.

INTRODUCTION

FEA is an important tool for modelling and evaluating structural and component behaviour, forecasting design performance under different loading circumstances, improving performance, and assuring structural integrity. Advances in Finite Element (FE) modelling approaches have made it possible to simulate complicated structural reactions (Liu, Li and Park, 2022). However, higher computational power and more efficient techniques have resulted in increasingly complicated FE models. This complexity, together with the requirement for comprehensive geometry and mechanical characteristics, renders extremely detailed FE models impracticable for large and complex structures, particularly when considering uncertainties in structural factors such as mechanical properties.

Nonlinear material analysis with uncertainty is critical in structural engineering. Nonlinear analysis considers significant deformations, material and geometric nonlinearities, resulting in a more realistic perspective of structure reactions (Luu, Bui and Kim, 2023). Nonlinear material analysis and stress-strain interactions present substantial modelling and analytical issues for linear systems, necessitating sophisticated approaches. Material and geometric nonlinearities have practical ramifications because they increase uncertainty and unpredictability in structure reactions, making performance prediction and control more difficult. Uncertainty analysis in complex structural systems is critical for risk assessment and decision-making since it provides useful insights into model output uncertainties and identifies potential risks (Hong and Zhongmin, 2023).

The purpose of this study is to create a computational model for one-dimensional bar components using Excel VBA. The existing code is changed to accommodate fuzzy and random theories, as well as FRV representation in FEA. The model looks at nonlinear stress and strain under hybrid uncertainty settings. This study focuses on the application of FEA to structural models with nonlinear material characteristics, with a particular emphasis on the link between stiffness and nonlinear behaviour. The significance of this study stems from the fact that many engineering applications cannot be accurately modelled using a linear framework. It alters design and analytical methodologies for structures susceptible to nonlinear material behaviours and uncertainties, resulting in safer and more efficient designs in sectors where unpredictability is prevalent.

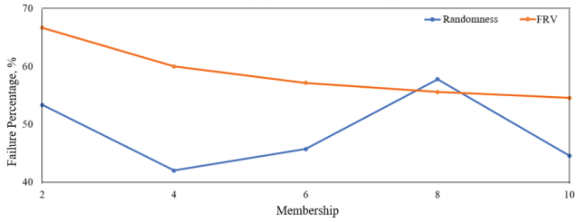
RESULTS AND DISCUSSION

The bilinear kinematic model technique (Huang, Kyvelou and Gardner, 2023) shown in equation (1) served as the primary guidance for further investigation of nonlinear material characteristics. The measured material properties of WAAM HSS (Huang *et al.*, 2022) shown in Table 1 are taken for use of uncertainty propagation in the structural analysis of nonlinear material behaviour by randomness as well as FRV.

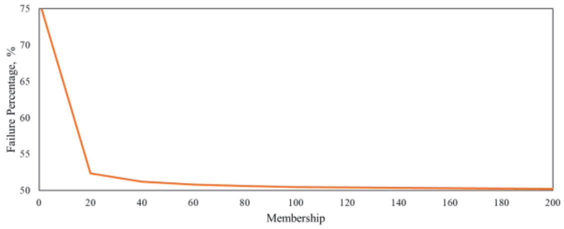
$$\varepsilon = \begin{cases} \dfrac{f}{E} + 0.002\left(\dfrac{f}{\sigma_y}\right)^n & \text{for } f \leq \sigma_y \\ \dfrac{f-\sigma_y}{E_{0.2}} + \varepsilon_u\left(\dfrac{f-\sigma_y}{\sigma_u-\sigma_y}\right)^m + \varepsilon_{0.2} & \text{for } \sigma_y < f \leq \sigma_u \end{cases} \tag{1}$$

Table 1. Measured material properties of WAAM HSS coupons (M = Machined; AB = As-built) used for comparison with predicted stress-strain curves

Label	**Surface**	**Feedstock wire**	t_{nom} **(mm)**	**θ (°)**	**E (MPa)**	f_y **(MPa)**	f_u **(MPa)**	n	m
HS-M-2-90	M	E120C-GH4	2	90	204000	842	1004	33.1	2.3
HS-M-3-90		ER110S-1	3	90	223800	705	841	7.1	1.9
HS-M-5-90		800 MPa	5	90	206388	776	846	17.7	3.0
HS-AB-8-0	AB	ER110S-G	3	0	220800	671	731	14.5	1.5
HS-AB-3-45		ER110S-G	8	45	214200	633	721	12.2	2.0
HS-AB-3-90		ER90S-B91	3	90	190600	671	754	12.7	3.0



(a)



(b)

Figure 1 Graph of failure percentage against membership: (a) randomness versus FRV, (b) FRV

Failure trend is studied using two distinct input load techniques, randomness and FRV, with failure percentage computed for outputs surpassing mean yield strength of WAAM HSS (737.5 MPa). Figure 1 (a) demonstrates considerable changes in how the input data structure influences failure results. Random input behaves in a wave-like manner, with a variable failure percentage as the alpha segment grows, emphasising the difficulty in anticipating failure patterns.

In contrast, FRV input results in a constant drop in failure percentage from 66.67% to 54.55% with increasing membership, illustrating the effectiveness of a structured approach in lowering failure risk under uncertainty. Figure 1 (b) shows a constant fall in FRV failure percentage from 66.67% (alpha cut = 2) to 50.24% (alpha cut = 200), with limited additional reduction up to 1000 alpha, resulting in a value of about 50%. This situation can be related with the nature of FRV of mixing fuzziness and randomness, in which rising alpha reduces uncertainty and failure, reaching a critical equilibrium point of roughly 50% and optimising risk assessment in material structures.

CONCLUSION

The findings of study underline the importance of input data structure on failure rates. Random input data poses difficulties in predicting failure patterns owing to its variable failure percentage with increasing membership. This unpredictability highlights the difficulties of minimising failure risk through random inputs. The findings indicate that employing FRV input is a more organised and dependable strategy to decreasing failure risk at various uncertainty levels. The capacity of FRV to continuously lower the failure percentage and achieve a critical equilibrium point optimises risk assessment in material structures, making it a better technique than random input.

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