

From Materials Testing 1.0 to 2.0 for Fusion Materials

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Abstract. Nuclear fusion development is in the transition from conceptual to detailed design. This requires material data for multiple materials in extreme environments on aggressive timelines. Traditional (MT1.0) tests will not be able to provide the required data in time. A transition to multivariate tests that take advantage of full-field measurements and modelling is required to minimise the number of tests, whilst maximising the data gained per test. This is the philosophy of Materials Testing 2.0 (MT2.0). We describe current progress on developing MT2.0 style tests for specific fusion design rules and current application, beginning with Finite Element Model Updating (FEMU) for post-necking behaviour in small-scale uniaxial tensile tests and moving towards multi-ligament sample designs for fusion component design rule validation.

Introduction

Mechanical testing for fusion materials has traditionally focussed on miniaturising standard tests. Miniature specimens require less material and are easier to irradiate and handle post-irradiation. However, this approach still needs many tests and hence significant time to complete test campaigns. This contrasts with the aggressive timescale of proposed fusion reactors, with the UK targeting 2040 for a demonstration reactor [1]. Qualifying new candidate materials within this timeframe is unlikely to be achievable without a change of approach.

Progress has been made towards applying the MT2.0 philosophy [2] to accelerate fusion materials qualification. Finite Element Model Updating (FEMU) has been developed and applied to two cases: a small sized uniaxial specimen and a complex multi-ligament specimen.

Materials Testing 1 to 1.5

Design engineers need accurate constitutive laws for the materials used in the components being assessed. Uniaxial tensile tests only give valid data until the start of necking. Beyond this strain, the stress state becomes more triaxial and the strain rate changes. Due to the thick sections and constraint, real components could experience strains beyond the uniaxial uniform strain. Accurate elasto-plastic design assessment, particularly for off-normal and accident scenarios, requires information after necking.

FEMU has been applied to small uniaxial specimens to obtain post-necking true stress-strain from the tests already being conducted, nominally 'MT1.5'. Digital Image Correlation (DIC) has been used to measure the full-field surface displacements and form part of the cost function to be optimized. Particle Swarm Optimization (PSO) was used to optimize the model to take advantage of the parallelisation of FE solves. Two different thicknesses of sample were tested.

The uncertainty associated with the optimization process has been investigated. In particular, the influence of grey-level noise on the optimization accuracy using the MatchID FEDEF module. Work is underway to use data from the particle swarm runs to estimate the uncertainty on the identified flow curve for each specimen.

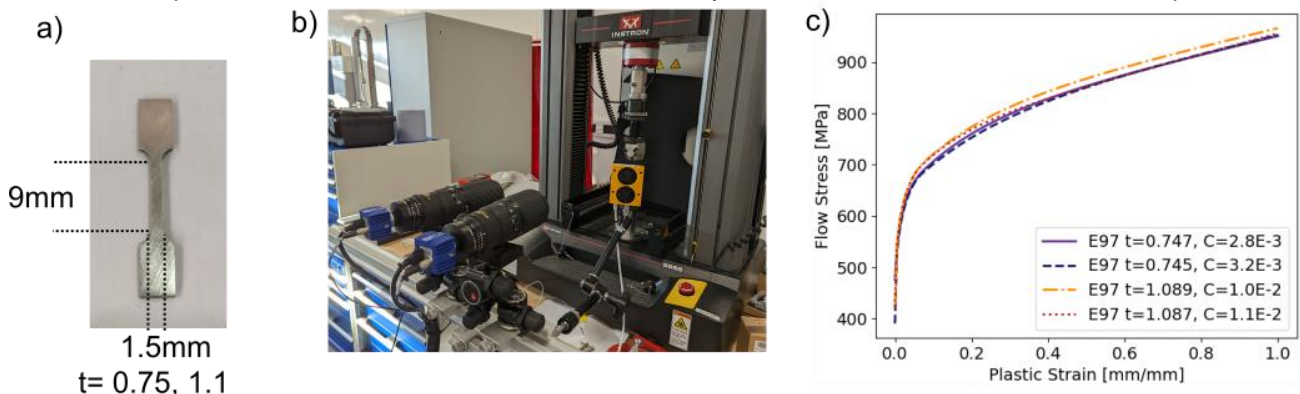


Figure 1: a) 'D-Mini' tensile sample, b) DIC testing setup, c) Identified flow curves for two specimens at each thickness, showing reasonable agreement between the two thicknesses.

Materials Testing 2.0 For Design Rules

Candidate designs for fusion reactors components are assessed against several design rules to determine lifetimes under different thermomechanical loading conditions. The uncertainty on these assessments is strongly dependent on the uncertainty of the input material data [3]. Due to the large test matrix and potential for time saving, the exhaustion of ductility design rule was targeted. This rule determines the failure envelope in triaxiality-equivalent strain space. Higher triaxiality reduces the strain at failure.

Traditionally this rule is calibrated by testing multiple round bar samples with notches of reducing radius to increase triaxiality. For the MT2.0 approach, a multi-ligament specimen was designed to target the exhaustion of ductility design rule. Multiple strains and triaxialities at failure occur on the same specimen. Successful identification of the plastic model and ductile damage model is demonstrated using Abaqus\Explicit and the MatchID FEDEF module.

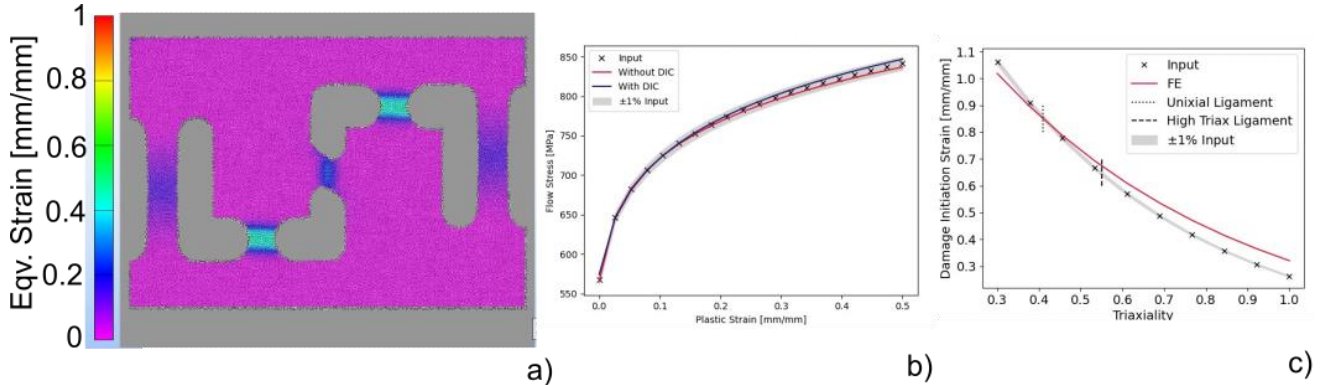


Figure 2: a) First iteration of specimen geometry showing DIC on FE deformed images, b) optimization of plastic model and c) optimization of ductile damage model.

Conclusions

Steps have been taken to introduce MT2.0 testing philosophies to materials testing for fusion applications. Post-necking equivalent stress-strain has been determined using FEMU on existing small-scale uniaxial test specimens. A novel multi-ligament specimen has been designed and trialled to determine the triaxiality-strain to failure limit in a single test. The aggressive timelines of fusion development offer an opportunity for the development of MT2.0 tests. However, significant effort will be required to demonstrate the robustness and advantages of MT2.0 over existing methods.

Acknowledgements

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References

- [1] "Site of UK's first fusion energy plant selected," 2022. <https://www.gov.uk/government/news/site-of-uks-first-fusion-energy-plant-selected> (accessed Apr. 18, 2023).
- [2] F. Pierron and M. Grédiac, "Towards Material Testing 2.0. A review of test design for identification of constitutive parameters from full-field measurements," *Strain*, vol. 57, no. 1, pp. 1–22, 2020, doi: 10.1111/str.12370.
- [3] J. H. You, M. Li, and K. Zhang, "Structural lifetime assessment for the DEMO divertor targets: Design-by-analysis approach and outstanding issues," *Fusion Engineering and Design*, vol. 164, Mar. 2021, doi: 10.1016/j.fusengdes.2020.112203.