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The Second Sandia Fracture Challenge: Blind Predictions of Ductile Fracture

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Introduction

Ductile failure of structural metals is relevant to a wide range of engineering scenarios. Computational methods are employed to anticipate the critical conditions of failure, yet they sometimes provide inaccurate and misleading predictions. Challenge scenarios provide an opportunity to assess the blind, quantitative predictive ability of simulation methods against a previously unseen failure problem. Rather than evaluate the predictions of a single simulation approach, the Sandia Fracture Challenge (SFC) relies on numerous volunteer teams in the broad mechanics community to apply a broad range of computational methods, numerical algorithms, and constitutive models to the Challenge. In the first SFC, a wide range of issues were raised in ductile failure modeling, including a lack of consistency in failure models, the importance of shear calibration data, and difficulties in quantifying the uncertainty of prediction (see [1] for details of these observations). This second installment of the SFC investigated the ductile rupture of a Ti-6Al-4V sheet under both quasi-static and modest-rate dynamic loading. Fourteen volunteer teams utilized a variety of computation methods, numerical algorithms, and constitutive models to predict the fracture path and quantitative far-field failure metrics such as peak force and displacement at crack initiation. The teams were provided a limited data set of tensile- and shear-dominated material calibration data, consistent with real-world engineering data, and the geometry and loading conditions of the Challenge geometry, which was a sheet with several holes and notches that led to a competition between tensile- and shear-dominated failure modes. Three independent test labs, including one post-blind assessment, quantified the experimental outcomes, and fourteen teams contributed blind failure predictions. These predictions were, on average, more consistent with the experimental outcomes as compared to the predictions in first SFC, but this second SFC identified several shortcomings in the predictions, to be presented below. The reader is invited to read a special 2016 volume of the *International Journal of Fracture* that describes the second SFC in detail [2], including individual articles by eight of the participating teams describing their post-blind assessment of their predictions. This extended abstract will provide highlights of the experimental observations, comparison of the predictions and experiments, a brief discussion of the results, and some conclusions.

Challenge Definition and Experimental Observations

The second SFC participants were asked to predict the crack path and the forces and displacements associated with crack initiation and propagation in the geometry, shown in Figure 1, designed so that there was not an intuitively obvious crack path. For this challenge, the material of interest was Ti-6Al-4V, a rate-dependent material; the challenge geometry was tested at two displacement rates, 0.0254 mm/s and 25.4 mm/s. The prediction teams were given five months to return their predictions. In this challenge, we aired on the side of providing more information than typically available in engineering scenarios to provide methods that needed more initial information a fair opportunity in their predictions. We provided engineering drawings with tolerances, actual dimensions of calibration and challenge geometry specimens, heat treatment details and hardness values, tensile tests and non-standard shear data tested at the displacement rates of interest, information about the grips, and deformed shapes and fractography. The challenge geometry was blindly tested in two independent labs with one lab testing after the predictions had been submitted. (a) Slow (0.0254 mm/s) Loading Rate
(b) Fast (25.4 mm/s) Loading Rate

Figure 2 includes the experimental test results for the slow and fast loading rates for the two Sandia labs; the results show agreement in their load versus crack opening displacement (COD) measurements. Seven of the eight samples tested at 0.0254 mm/s and all seven of the samples tested at 25.4 mm/s in the Structural Mechanics Laboratory failed along the B-D-E-A path defined in Figure 1, while one sample tested at 0.0254 mm/s failed along the A-C-F path. The Material Mechanics Laboratory tested three at the slow displacement rate and one at the fast displacement rate, and all failed along the B-D-E-A path. Based on factors related to geometry and fractography, it is considered that the failure along A-C is not the expected or nominal response of the specimen, and the correct failure path identified from the experiments is along path B-D-E-A (see [2] for more details.)

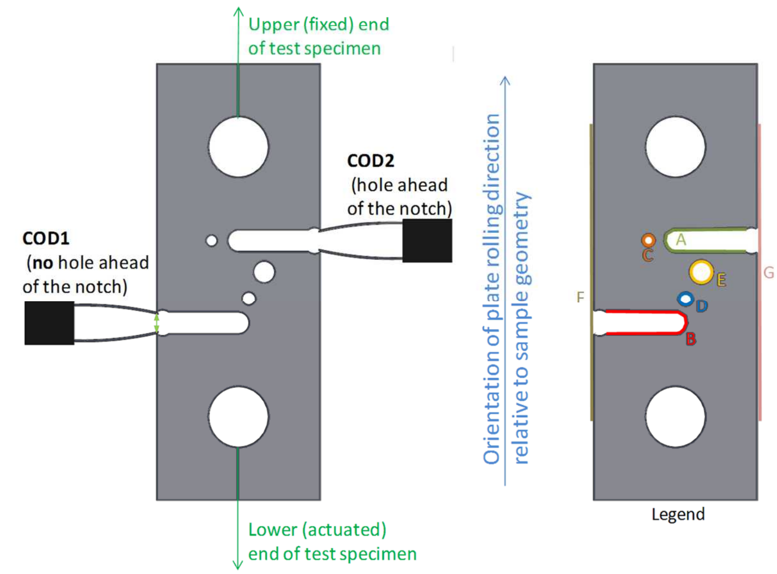
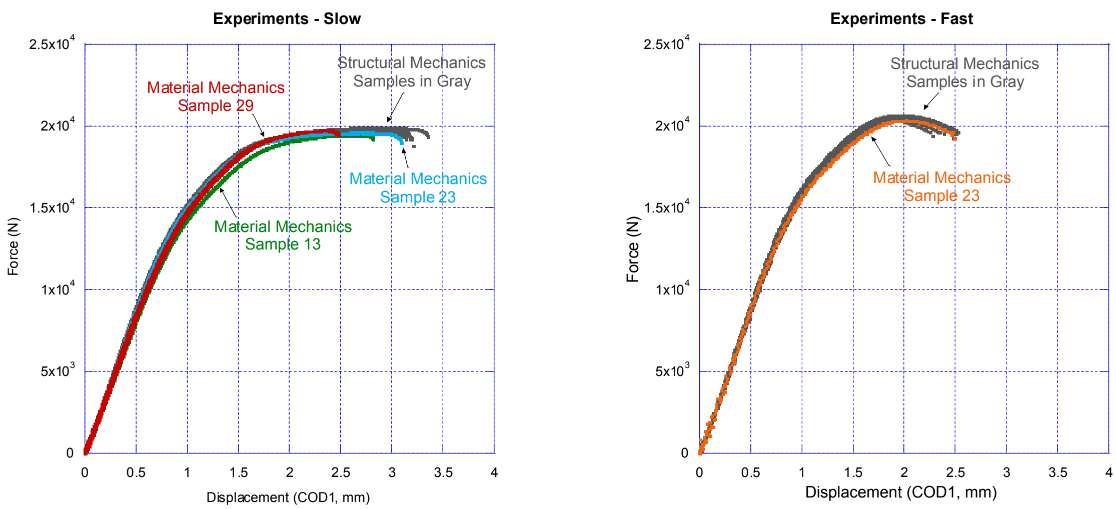


Figure 1. Plate orientation, actuation direction, Crack Opening Displacement (COD) gauges and legend of features labeled A-G.

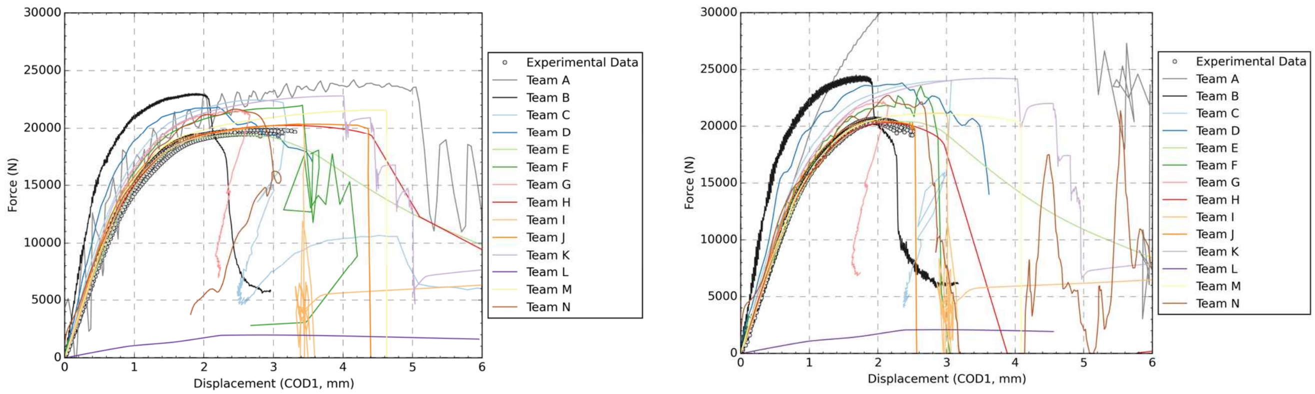


(a) Slow (0.0254 mm/s) Loading Rate (b) Fast (25.4 mm/s) Loading Rate

Figure 2. Comparison of force-displacement curves measured by the two Sandia mechanical testing labs.

Comparison of Predictions and Experiments and Discussion

The prediction teams showed great diversity in their modeling approaches leading to the variability in predictions. The areas where they made key modeling decisions included: computational method, solver type, coupling (thermal effects), boundary conditions, element type, discretization, fracture method, uncertainty bounds, yield function, hardening law, rate and/or temperature dependent plasticity, failure criteria, damage evolution, and material calibration data used. Figure 3 shows the predictions from the fourteen teams overlaying the experimental results in the circles for the two loading rates. The overall impression of the predictions is that there is a general improvement in the predictions as compared to the first external SFC. There appears to be less scatter in the initial behavior than in the previous challenge. Some of the striking features of these predictions are: there was one team that had very low predictions which were attributed to human error in summing the reaction forces at the nodes; eight out of fourteen teams predicted the behavior up to the peak load within 10% of the experimental scatter; teams tended to systematically overpredict stiffness and yield; and the post-necking behavior and crack initiation continue to be difficult to predict. Successful predictions were identified as those within 10% of the experimental bounds. There were seven teams that predicted the peak load. Five teams of those predicted the correct crack-path. Four of those predicted the correct load at crack advance, but overpredicted the COD measurement for at least one loading rate. In comparing the “successful” predictions, the general features were that their boundary conditions better mimicked the experiment, they used an anisotropic yield function, and they utilized both tensile and shear calibration data. These successful predictions did not have a consensus on thermal coupling, plastic hardening, failure criterion, or damage evolution, so further research is necessary to tease out these variables.



(a) Slow (0.0254 mm/s) Loading Rate (b) Fast (25.4 mm/s) Loading Rate

Figure 3. Combined comparisons of force-COD predictions (colored lines) to experimental observations (gray circles).

There were five main sources of discrepancies identified from the fourteen predictions: boundary conditions, plasticity model, thermo-mechanical coupling, failure criteria, and damage progression and fracture morphology. First, only basic information about the clevis-pin connection was provided to the participants, so they had to choose how they wanted to represent the pin-contact BC. Teams that chose fully constrained non-sliding pin contact tended to overpredict the stiffness and peak forces. Frictionless or free-rotating pint contacts appeared to better mimic the experiments. Second, the teams were provided tensile and shear data for the rolling and transverse directions of the Ti-6Al4V sheet that showed there was plate anisotropy; some of the teams did not utilize the shear data and used simple J_2 plasticity, ignoring the Lode-angle dependence of this material that has a softer yield in shear than in tension. This led to an overprediction in the yield / hardening behavior. Third, the challenge geometry exhibited more than a 60-degree temperature rise in the necking ligament for the fast rate test; not provided with any experimental thermal data, some teams ignored the effects of plastic-work induced thermal softening, so they did not capture the necking behavior. Teams that somehow dealt with the thermal work tended to capture some aspects of the necking behavior. Fourth, there was no consensus on what failure parameter to use for this problem that showed a competition between a tensile and shear-dominated failure. The teams that utilized shear data and calibrated a triaxiality-dependent failure model tended to be more accurate. Providing tensile data and a fracture toughness test would not have been sufficient to calibrate such models. Fifth, some approaches could not capture the unstable crack growth and did not properly characterize the resistance of the material to crack growth. No approach could capture the three-dimensional nature of a fracture surface.

Conclusions

Overall, the SFC provides a unique platform for collaborative assessment of how well we can predict ductile failure. The SFC documents what the state of the art in predictive capability for a realistic engineering-type problem, providing evidence to support use of codes in engineering problems and educating analysts who use but do not develop these methods. The SFC illustrates many of the key deficiencies in structural mechanics predictions, demonstrating that fracture is not a readily “solved” problem in some cases, motivating mechanicians and code developers to fix deficiencies, and guiding investments to improve capabilities. The SFC also raises the international awareness of the need to improve these capabilities, directing funding back into fracture mechanics research, revitalizing the prestige in working on failure of structural metals, and establishing well-documented “toy problems” for future assessment and benchmarking.

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[1] Boyce, B.L., et. al., The Sandia Fracture Challenge: blind round robin predictions of ductile tearing. *International Journal of Fracture* 186, 5-68, 2014

[2] Boyce, B.L., et. al. The Second Sandia Fracture Challenge: Predictions of Ductile Failure under Quasi-Static and Moderate-Rate Dynamic Loading. *International Journal of Fracture.* DOI 10.1007/s10704-016-0089-7, 2016.