Combined Numerical And Experimental Evaluation Of Shear Damage Interaction Between Torsional, Tensile And Compressive Loading Modes

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Introduction: Skeletal diseases such as osteoporosis impose a severe socio-economic burden to ageing societies. Decreasing mechanical competence causes a rise in bone fracture incidence and mortality especially after 65 years old. At the hip, 90% of all fractures are related to falls and a third of people over 65 fall annually. Every hip fracture starts in the vicinity of, or induces, bone damage and the load direction during a fall is distinct from the loading of daily activities. The mechanisms of how bone damage is accumulated under different loading modes and its impact on bone strength are only partially understood, especially when shear is involved. An earlier study on tensile and compressive loading shows that damage accumulated in one loading mode will affect the mechanical properties in another [1]. To extend this we hypothesised that shear damage has no impact on the mechanical properties of tensile or compressive loading and vice versa. Since torsion represents an inhomogeneous load case, we present a combined numerical and experimental study, using data from [1], to evaluate the shear damage behaviour.

Materials and Methods: Ten dumbbell shaped samples were tested monotonically beyond yield in torsion by controlling twist angle with torque recorded (MTS Mini-Bionix 858 & Epsilon Tech 3550HT), see [1] for details of sample preparation and form. The data was used to identify stiffness, yield point and hardening behaviour. Low cycle, large amplitude (0.52% plastic strain) overloading in torsion with subsequent interrogation tests in tension and compression was used to determine the damage behaviour. This cyclic testing consisted of 12 samples using the same apparatus as the monotonic testing. The parameters were used to identify and verify a finite element model (SIMULIA Abaqus) featuring an elastic-viscoplastic constitutive material model from [2]. This was used to interpret a series of tests where overloading was applied in torsion, tension or compression with subsequent interrogation in another loading mode. These interactions, see [1], were used to identify the impact and interaction of evolving damage, calculated as $D = 1 - \epsilon_i / \epsilon_0$ within a loading mode, where D is damage as a ratio, ϵ_i the elastic stiffness after overloading step i, and ϵ_0 the elastic stiffness before any overloading.

Results: The numerical model fits to the monotonic and overloading experimental data (Figure 1). It allows identification of damage and accumulated plastic strain, giving an indication of the accumulation of damage in torsion, and how this compares to cyclic overloading in pure tension or compression. Further results indicate that overloading in torsion has an impact on compressive and tensile load cases, and vice versa. For torsional overloading, 46% damage at 0.52% plastic strain is detectable as a reduction in stiffness of 14% in tension and 20% in compression.

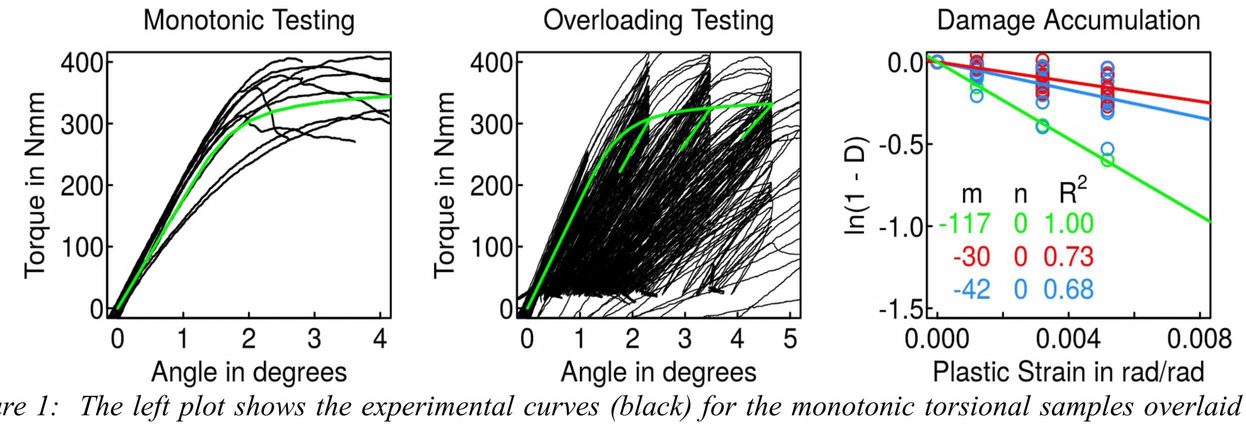

Figure 1: The left plot shows the experimental curves (black) for the monotonic torsional samples overlaid with the numerical curve (green). In the centre experimental curves (black) for the torsional overloading are overlaid with the numerical result (green). Damage accumulation, the natural log of 1 - D, for overloading in torsion (green) along with elastic testing in tension (red) and compression (blue) is seen to the right [1].

Discussion: The finite element model has been successfully combined with the experimental results for the torsional testing, allowing the evolution of damage to be investigated. Results indicate the hypothesis that torsional overloading does not affect subsequent loading in tension or compression has to be rejected due to the damage accumulation seen between the loading modes. The inhomogeneity within the torsional loading case can now be accounted for using the verified numerical model. The results could be used to further the understanding of bone fractures, specifically verifying the accuracy of computational fracture risk analyses with multiple loading modes.

References: [1] Mirzaali et al, *J Mech Behav Biomed Mater*, 2015, 49, 355-369. [2] Schwiedrzik and Zysset, *Biomech Model Mechan*, 2013, 12, 201-213.