Acta Materialia 149 (2018) 78–87

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Effects of nodal fillets and external boundaries on compressive response of an octet truss

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ARTICLE INFO

Article history:
Received 13 September 2017
Received in revised form
20 December 2017
Accepted 21 December 2017
Available online 13 February 2018

Keywords:
Cellular solids
Computer simulations
Digital image correlation
Mechanical property

ABSTRACT

Additive manufacturing has enabled fabrication of weight-efficient periodic trusses over a wide range of length scales. The principal objective of the present study is to address two coupled aspects of truss design and performance: (i) the extent to which circular nodal fillets enhance node stiffness and alleviate stress concentrations, and (ii) the extent to which external boundaries affect local strut strains. To this end, octet trusses with and without filleted nodes were fabricated out of a hard thermoplastic and tested in compression, with digital image correlation used to monitor axial and bending strut strains and nodal rotations. Complementary finite element simulations were also performed. Macroscopic compressive failure occurs through bending and buckling of certain inclined struts followed by *tensile* rupture of struts oriented perpendicular to the loading direction. The struts experiencing the highest tensile strain and most prone to rupture are those located along the truss mid-plane and that intersect external edges. Additional boundary effects are manifested in exacerbated nodal rotations and bending of inclined struts intersecting the truss corners. Although buckling begins in the affected struts, large-scale buckling is preceded by tensile rupture. The implications for design and failure prediction of finite truss structures are discussed.

1. Introduction

Although periodic truss (or lattice) structures are generally preferred over stochastic foams in structural applications, they are more difficult to fabricate using conventional casting, forming or machining operations, especially when the constituent struts are slender and the structures comprise arrays of many unit cells in three directions. Additive manufacturing (AM) has played a transformational role in this regard [1]. AM methods previously employed for fabrication of truss structures include fused deposition modeling [2], selective laser sintering [3], electron beam melting [4–6], stereolithography (SLA) [7], and self-propagating photocuring [8]. Build volumes of commercial systems typically range from 0.001 m^3 to 1 m^3. Sub-mm minimum feature sizes and print resolutions of tens of μm are now routinely achieved. Therefore, in addition to enabling fabrication of even the most complex trusses, AM allows fine control of structural features and tailoring local geometries in ways that were heretofore unimaginable.

Analyses of truss properties (*e.g.* stiffness, strength, toughness) have largely focused on effects of topology in notional truss *materials*: aggregates of many struts with dimensions much smaller than macroscopic scales of interest. A tacit assumption is that the response of the material can be addressed by considering a small representative volume element, typically one unit cell. Although this approach is useful in identifying broad trends in behavior and establishing baseline properties, it fails to capture important effects that come into play in real (finite) truss *structures*. The current study focuses on two such effects: (i) the presence of external boundaries and (ii) the geometry of nodal regions at which struts intersect.

Nodal connectivities of struts that terminate at external boundaries are lower than those in the bulk. Consequently, near-boundary stiffness and strength may differ from the corresponding bulk properties. The effect persists to a depth that scales with strut length and depends sensitively on truss topology.

Effects of boundaries on elastic properties of truss structures have been studied through finite element calculations of large aggregates of unit cells [9,10] and through novel application of Bloch

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https://doi.org/10.1016/j.actamat.2017.12.060
1359-6454/

wave theory [11]. Studies on 2-dimensional elastically-isotropic trusses have shown that, in fully triangulated and hexagonal structures, the thickness of the elastic boundary layer is comparable to the strut length and the layer has negligible influence on the elastic properties of finite-sized structures. In contrast, the 2-dimensional regular Kagome structure (which is also elastically isotropic) exhibits a thick boundary layer when loaded in certain directions; the thickness of this layer is inversely proportional to truss relative density. The effect is a manifestation of the transition from a stretch-dominated mode of deformation in the bulk to combined bending and stretching along some boundary planes. Interestingly, when long cracks are present, boundary effects in the latter case cause a reduction in crack tip stresses and lead to an unusually high fracture toughness [9]. Computational studies on 3-dimensional octet trusses have similarly shown that the boundary layer is negligible [10] and that the stiffness and compressive buckling strength are independent of truss size [12]. Notwithstanding, we show in the present study that important boundary effects occur along the *edges* of octet trusses. Although benign with respect to global elastic response, the effects play a crucial role in compressive failure when the strut material has limited ductility.

Little attention has been focused on the effects of node geometry on truss properties. A cursory inspection of the intersection of struts reveals the issue: the axial loads transmitted through the struts must be transmitted through nodes at which the load bearing area is lower because of the overlapping strut volume. One consequence is that, if no provision is made for the area reduction, yielding (when it dominates) initiates within the nodal regions, not within the struts themselves [13,14]. Under compressive loads, this localized plasticity may be stable, leading to lateral expansion of the nodes under progressively increasing load and to eventual yielding of the struts [13]. In contrast, under tensile loading, local yielding within the nodes is likely to lead to strain localization before global strut yielding (except in cases where the work hardening rate of the constituent material is unusually high).

Effects of node geometry may be more nuanced in cases in which the strut slenderness ratio is particularly high. Absent yielding, the conditions for strut buckling under macroscopic compression depend on the (elastic) stiffness of the nodal region. (The effect can be couched in terms of the effective-length factor in Euler buckling theory; a topic we return to in due course). If node yielding precedes buckling, the constraints acting on the strut ends are reduced and thus the buckling strength is also reduced.

In addition to the effects of reduced cross-sectional area associated with strut intersections, changes in cross-section invariably lead to local stress concentrations. These concentrations may become important in cases in which the struts are loaded in tension and in which the strut material has low tensile ductility. Established design principles for stress concentration reduction employing gradual transitions in area [15], such as those obtained with the use of fillets, are expected to mitigate the problem to some extent.

From another perspective, truss failure can be considered in terms of the stability of deformation as localized failure events accumulate. When the load-bearing capacity is dictated by elastic buckling of a family of struts that are equally strained, the macroscopic truss strength is dictated by the volume-averaged strut stress once all struts have buckled. Because the stress needed for continued buckling of an elastic strut is constant (*i.e.* the compressive response is essentially elastic, perfectly-plastic), a premature buckling event caused by a structural imperfection does not affect the ultimate truss strength. Analogously, in cases where the strut slenderness ratio is small and the nodal regions are augmented to mitigate the area reduction caused by strut overlap, the truss strength is dictated by the material yield strength and the load bearing area of all struts. Here, again, local structural defects or stress concentrations that may cause localized yielding should not affect truss strength. These represent best-case scenarios.

In an alternative scenario, where the material is relatively brittle and its strength follows weakest-link scaling laws, strut fracture is expected to be stochastic and controlled by extreme values in the stress distribution and the volumes over which such stresses persist. For example, local stress elevations in nodal regions may cause local fracture, leading to load shedding and potentially additional fracture events in neighboring regions. In one limit, where the truss is comprised of only a small number of unit cells (and hence a small number of struts), the first strut fracture event may lead to instability and catastrophic truss failure. The truss strength would therefore be inherently stochastic. Conversely, if the macroscopic structural dimensions greatly exceed the unit cell dimensions and the truss is designed to exhibit some degree of damage tolerance (*i.e.* toughness), a single localized failure event may not be critical to structural stability.

The principal goal of the present study is to address the effects of nodal fillets and external boundaries on the compressive response of octet trusses made from a hard thermoplastic. The article is structured as follows. Materials and test methods for the experimental study are described in Section 2. The structure of a finite element (FE) computational model is presented in Section 3. Experimental and computational results of macroscopic stress-strain response and of strut strains and nodal rotations are presented in Section 4. This is followed by a discussion of the results and the implications for truss design and failure prediction, in Section 5.

2. Materials and test methods

Specimens of the specific octet truss $\{2FCC\}^2$, *i.e.* a $2 \times 2 \times 1$ tiling of face-centered cubic unit cells following the truss taxonomy outlined in Ref. [16], were fabricated both with and without rounded fillets (Fig. 1). The struts were designed to have a circular cross-section with radius $r = 1$ mm, length $l = 20$ mm and slenderness ratio $\ell/r = 20$. Fillets (when employed) were designed with a constant radius of 2 mm. The relative densities, $\overline{\rho}$, were approximately 0.082 and 0.090 for trusses with and without fillets, respectively.

The trusses were printed using a production-level, through-vat stereolithography machine (ProJet 6000, 3D Systems). Print resolution is 50 μm in the build direction (z) and 75 μm in the two transverse directions (x and y). The material used in this study is VisiJet SL Clear, a hard polycarbonate-like material with a reported ultimate tensile strength $\sigma_o = 52$ MPa, Young's modulus $E_o = 2.56$ GPa and an elongation at break $\varepsilon_f = 6\%$. Auxiliary support structures were automatically generated in 3DManageTM (3D Systems) with an angle constraint of 36°. Upon completion of the build, the fabricated parts were immersed in a bath of isopropyl alcohol (IPA) for 10 min. Auxiliary support structures were then manually removed and the parts were re-immersed in the IPA bath for an additional 10 min. Following extraction from the bath, the parts were placed in an ultra-violet finishing chamber for 30 min. Photographs of the trusses, including comparisons of the nodal regions in the computer models and in the printed parts, are shown in Fig. 1. These comparisons attest to the high printing fidelity. Nodal regions of both sample types are accurately reproduced in the finished parts. Surface steps due to the layer-by-layer build process are on the order of the layer thickness (50 μm).

Uniaxial compression tests were performed perpendicular to the build direction at a nominal strain rate of 10^{-4}s^{-1}. Full-field displacement measurements were obtained using 3D digital image correlation (DIC) (Vic-3D, Correlated Solutions, Columbia, SC). Prior to testing, random speckles with a diameter of approximately