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Minimum mass design of thin tubular structures under eccentric compressive loading

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ABSTRACT

A minimum mass design study applicable to thin circular tube is performed for various modes of eccentric compressive loading. Axial crushing failure mode, frequently noticeable in uniform axial compressive loading of thin circular tube, does not appear in eccentric compression. Hence, other compressive failure modes, e.g., global buckling, yield and local buckling are studied with respect to non-dimensional load and geometric shape factors for a fixed-free condition. These modes are predominant in ductile engineering alloys. A failure mode map in terms of non-dimensional load and shape-factor for a given load-eccentricity are obtained and the prescription for minimum mass is given.

1. Introduction

Material efficiency attracted enhanced interest of researchers in recent times. A low material design ensures reduction in material cost, embodied energy, green house gas emission and life cycle impacts. Moreover, it serves the national interests, such as, less extraction of raw materials, lesser dependence on imports and increased self-reliance. Hence, scientists have explored the ways on how to make a design with less material for long time. In this perspective, shape efficiency based design plays a prominent role. Higher shape factor of a structure indicates its enhanced shape efficiency in terms of material consumption in comparison to a low shape factor based structure under same magnitude of load. Generally, the more slender the shape, the larger the weight savings; but there is a limit; making a product too thin and it will buckle—so there is a maximum shape factor for each material that depends on its mechanical properties. Shape efficiency based design is additionally dictated by manufacturing constraints. Many different shapes can be produced out of metals; but for some other structural material families, such as, for composite materials, manufacturing constraints play a wider role due to complexity in their processing and manufacturing routes. Thus, composite materials cannot be designed with as high shape factor as metals. Individual metal–matrix, polymer composite or other material also has their own distinct maximum attainable shape factor which ultimately determines how thin a section can be designed out of that particular material. For example, cast iron, austenitic, BS grade F1 material has an elastic bending shape factor of 24 which indicates the most efficient shape made of this alloy can attain maximum 24 times resistance to elastic bending (stiffness) deflection in comparison to a solid beam of circular cross-section of the same area [1]. Following the conservative design guideline, a section made with this alloy may not employ this maximum possible shape factor of 24; but it is certain that material consumption and, hence, the cost and companion life cycle impacts can be greatly reduced with an increased shape factor while maintaining the same stiffness as the beam of a square cross-section. Thus increased shape factor can intensely contribute to increased material efficiency. Hence, designers have focused on product designs with various efficient shapes; e.g., tubular, box, I-section, etc.

Few research groups also focused on shape efficiency based non-dimensional failure plots under various modes of failure. Weaver and Ashby [2] demonstrated competitive failure plots based on global buckling, yield and local buckling compressive failure modes in pursuit of optimal shape efficiency based design. In addition to

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Nomenclature

ρ	density of material
σ	failure strength of thin shell structure
σ_b	maximum compressive stress due to bending moment
σ_c	uniform compressive stress due to axial load
σ_{gb}	global buckling failure stress
σ_{lb}	local buckling failure stress
σ_y	yield failure stress
σ_{ys}	yield strength of the material
ψ	solidity ratio
υ	Poisson ratio
α	thin shell strength reduction factor
ϕ_B^e, ϕ	elastic bending shape factor; also indicates ratio between radius and thickness
ϕ_{opt}	optimal shape factor
γ	thin shell safety factor
c	distance from bending neutral axis to outer surface
e	eccentricity
$\bar{e}$	eccentricity ratio
m	column buckling mode parameter with expression of: $m^2 = P/EI$
m_{gb}	mass with respect to global buckling equation
m_{lb}	mass with respect to local buckling equation
m_{min}	minimal mass
m_y	mass with respect to yield equation
r	radius of thin shell
r_g	radius of gyration
$t/2$	blade shell thickness
t	thickness of thin shell
w_{max}	maximum transverse displacement in global buckling mode
A	cross-sectional area
D	diameter of thin shell
E	Young's modulus of material
L	length of thin walled structure
L_{eff}	effective column length
P	axial load
P_{avg}	average crushing load
X_1, X_2, X_3	eccentricity based factors

these three failures, Meidell [3] focused on another failure mode, i.e., axial crushing based compressive failure in his manifestation of shape efficiency based design. The later article particularly focused on detailed shape efficiency and optimal mass based design procedure as varies with load and shape factor based on aluminum. In another article, Rothwell [4] studied how the dimensions of an offshore tubular member can be changed in pursuit of wave loading reduction based on shape efficiency and buckling load constraints. All these above-mentioned studies, however, only focused on uniform compressive loading; whereas, in real life, many engineering structures and products frequently encounter various modes of eccentric compressive loading rather than uniform compressive one. Wind turbine tower is a typical example of such scenario whereby nacelle weight remains at an eccentricity to the tower neutral axis and this load eccentricity shifts the competitive failure boundary regions in a typical failure plot which ultimately affects optimal dimension based design issues. Additionally, various compressive failure modes also show different patterns under eccentric loading with reference to uniform compressive loading scenario. However, to the best of author's knowledge, no published literature so far focused on any failure mode map with all eccentric compressive loading together. Hence, an eccentric compression based failure plot is necessary to find the optimal shape efficiency based designs for similarly loaded thin shell structures. This article, accordingly, focuses on various leading eccentric compressive failure modes to determine the shape efficiency based failure plots based on non-dimensional factors.

2. Competing failure modes in eccentric compressive loading

Thin-walled tubular structures under compressive loading can fail by any of the following mechanisms based on the material properties and geometry: (i) onset of plasticity or yield failure, (ii) global buckling, (iii) local buckling, (iv) axial crushing, (v) inversion of shell, (vi) splitting of shell, etc [5]. Inversion of shell or invertube failure and tube splitting occur only when there is a die shape arrangement inside the hollow section of a thin shell structure which is not the case under study. Hence, plastic flow of material, global buckling, local buckling and axial crushing are the remaining dominant compressive failure modes. Out of these, plastic failure occurs when the structure can no longer bear any higher loading after its critical yield strength property. Global buckling failure occurs when the tubular column length exceeds a critical dimension. Eccentricity condition does not affect the critical global buckling load; however, the stress developed in an eccentric condition is different than non-eccentric uniformly distributed or point load condition. Other than this, local buckling mode is also affected by eccentricity. Liu et al. [6] explored various eccentric conditions on local bucking of steel tubular column and found that ultimate failure load greatly reduced with an increasing load eccentricity. Apart from eccentricity effect, local buckling defines a limit on how much thin a section can be made. Usually, for a given cross-sectional area, a higher amount of inertia can be obtained with a thin-wall section which reduces its mass eventually. However, if the shell section is too thin, local buckling occurs even before overall column buckling or yielding. Axial crushing is another prominent compressive failure mode for ductile thin wall structures which differs from usual yield failure with accompanying distinct mode shapes (e.g., diamond mode, ring or concertina mode, mixed mode). Since the pioneering work of Pugsley and Macaulay [7], Alexander [8], number of researchers and scientists focused on the study of this failure mode with corresponding energy dissipation and crashworthiness evaluation. Accordingly, axial crushing is seen to occur in circular tube [8], square tube [9], tubular ring [10], honeycomb cells [11], multi-corner columns [12], stepped thin-walled tubes [13], corrugated tubes [14] and many others. Out of these, thin shell structures are commonly used in energy and vibration absorption systems because of their stable plastic collapse mechanism and comparatively high energy absorbing capacity.

Within the failure modes, critical failure loads of global buckling, local buckling and yield failure for a thin shell structure are available in literature. However, axial crushing for the same is still to be explored in case of eccentric compressive loading. Hence, axial crushing failure is studied first to examine whether it is possible in case of eccentric compressive loading.

2.1. Axial crushing in eccentric compressive loading

2.1.1. Application of eccentric compressive loading

Applying non-uniform loading on a tubular structure based on a usual universal testing machine is not straightforward. Uniaxial mechanical characterization testing frame only provides uniform axial loading for one axis. Hence, adjustments are made by attaching a three-point bending jig of 100 kN load bearing capacity to a uniaxial mechanical testing machine. One of the two bottom