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Parametric design of multi-cell thin-walled structures for improved crashworthiness with stable progressive buckling mode

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ABSTRACT

Thin-walled single and multi-cell structures are an ongoing topic of interest in the field of crashworthiness, due to their wide range of applications in automotive and aerospace industry as lightweight energy-absorbing structures in crash environments. This work presents a new five-cell cross-section that merges high performance multi-cell and twelve-edge cross-sections from previous research, and compares its performance to four- and nine-cell square cross-sections. Super Folding Element (SFE) theory and Finite Element Analysis (FEA) in LS-DYNA are used to analyze cross-sections and found to have good agreement. The LS-DYNA environment is validated with physical testing. The geometry of the cross-sections is varied in order to find maximal values of the performance parameters *specific energy absorption* (*SEA*) and *crush force efficiency* (*CFE*) under stable progressive buckling mode and constraints for manufacturability. The nine- and five-cell cross-sections ultimately out-perform the four-cell cross-section, with the nine-cell having the highest *SEA* and *CFE*, though the five-cell design has a significantly lower (47%) *mean crush force* (P_m) for only an 11% and 14% loss in *SEA* and *CFE* respectively. As a final refinement, the geometry was varied across these two high-performing cross-sections to create equivalent mean crush forces to the four-cell cross-section, which showed the five-cell cross-section to have an improved *SEA* and better mass efficiency over the nine-cell under a mean crush force constraint.

1. Introduction

Thin-walled single and multi-cell structures have generated significant interest due to their high energy-absorbing characteristics, low weight, inexpensive manufacturing, and crashworthiness applications within the automotive and aerospace industry. In particular these tube-shaped structures have been implemented widely in the structural frame of vehicles as frontal impact energy absorbers. The value of these structures as energy absorbers was first explored by Alexander [1] as well as Pugsley and Macaulay [2] and Magee and Thornton [3]; Alexander in particular proposed the first theoretical model for characterizing the plastic collapse of thin-walled structures with one folding wave and stationary hinge line in [1]. Alexander's theory was expanded by Abramowicz and Jones [4] and by Weirzbicki and Bhat [5,6] which added moving hinge lines to the model. Abramowicz expanded on this theory by also introducing the concept of effective crushing distance [7]. Much of this early research focused on the collapse of circular tubes, which was later expanded to square tubes through the work of Abramowicz and Jones [4,8,9]. The addition of dynamic effects to this model was later developed by Hanssen [10]. Notably, these folding theories and subsequent models rely on the observed behavior of stable progressive buckling, whereby a structure undergoes periodic "folding" in order to maximally absorb energy.

The next theoretical advancement, Super Folding Element (SFE) theory, was proposed by Abramowicz and Weirzbicki in [11,12] and advanced in [13]. This theory, which combines concepts from plasticity with moving hinge line collapse theories, is foundational for modern theoretical models used to predict the collapse parameters (mean crush force, energy absorption, and folding wavelength) of structures with geometries consisting of single-cell cornered cross-sections (e.g. square, hexagonal). Notably, this theory was limited to two-flange corner elements, until expanded by Najafi and Rais-Rohani to include three flange "T" shaped elements meeting at various angles; this approach was based on observed behavior in numerical simulation [14,15]. A simplified folding element model using a reduced number of energy mechanisms from standard SFE was proposed by Chen [16] and expanded by Zhang [17] in order to also model "T" and "criss-cross" elements with three or four-flange elements. Preliminary work from Zheng [18] also presented SFE models for "T" and "criss-cross" elements, as well as derived equations to support variable wall thicknesses. The work by

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Chen, Zheng, Zhang, and Najafi has enabled the advanced modeling of more geometrically complex cross-sections consisting of multiple cells.

As the theory to predict the behavior of multi-cell cross-sections has advanced, so have the processes that enable the manufacture of multi-cell structures. Early research was limited to welded steel square and "top-hat" cross-sections as well as extruded shapes [4,8,9,19–21], though later works looked at more complex welded cross-sections [22]. More recently the ability to extrude geometrically complex single and multi-cell aluminum structures has increased interest in refining the design of these more complex structures. This manufacturing process also provides some limitations on the design space, as, for example, conventional machining guidelines do not recommend extruding aluminum shells with wall thickness less than 1 mm (0.040 in) [23]. Furthermore, more complex geometry like multi-cell cross-sections tend to have further restrictions on wall thickness in order to allow for proper flow of material. Cross-sections that utilize variable wall thickness, either axially or laterally, have been proposed and tested as in [18,24] using either tailor rolled blank (TRB) technology as initially proposed in [25], or Electrical Discharge machining (EDM). While TRB technology is promising and opens new avenues for design, it is limited in application to single-celled cross-sections at the moment. EDM, however, can produce multi-celled cross-sections, but is used primarily as a prototyping method rather than a mass manufacturing method, rendering it less suitable for automotive applications. Comparatively, extrusion is a widely available process common to mass manufacturing, capable of producing both single and multi-celled designs, and therefore a desirable process to use for the immediate implementation of new structural elements. Fang considered the use of extrusion to produce cross-sections with functionally graded thickness in [26], but was unable to produce cross-sections with non-uniform wall thickness, resulting in the inability perform physical testing on high-performing cross-sections found through numerical simulations. When evaluating these structures for applications in automotive collisions, manufacturing presents constraints on what cross-sections can be practically implemented and should be duly considered.

However, in addition to advancing manufacturing techniques, more work has been done on generally improving the comparative performance of thin-walled energy-absorbing structures. Early investigation into designing optimal multi-cell aluminum cross-sections by Kim [27] focused on improving single and multi-cell structures by maximizing specific energy absorption (*SEA*). Kim focused on single, double, triple, and four-cell cross-sections, as well as a new five-cell cross-section with square corners, and compared them to demonstrate the superior performance of multi-cell cross-sections. Furthermore, Kim addressed the problem of inducing the stable progressive buckling mode addressed by previous theoretical models through the introduction of triggers. Tang [28] proposed even more complex cylindrical multi-cell cross-sections and again demonstrated the improvements over conventional square and circular cross-sections. Chen and Masuda expanded this work to include multi-cell hexagon sections [29]. Additional comparative work on multi-cell cross-sections was performed by Song in [30], who also produced windowed structures to reduce peak force. Wu [31] expanded upon Kim's work in optimizing five-cell cross-sections, and demonstrated their good performance in comparison to four-cell and single-cell structures through numerical simulation and physical testing. Chen introduced a further variation on five-cell cross-section geometry by combining circular corners and orthogonal internal webs [32], noting that corner cell geometry can have a large impact on the structure performance. Alternate optimization techniques have also been used to develop the relationship between common crashworthiness performance parameters and structural geometry, such as shell thickness and cross-section width, as can be seen in [31,33,34]. Further works explored number of cells in multi-cell cross-sections for square, hexagonal, and hierarchical honeycomb structures under axial and oblique loading cases [35–37], with the general finding that multi-celled cross-sections outperform single-cell cross-sections, and higher numbers of cells also improve results. Topology optimization using finite element analysis and various algorithms was also performed on square and hexagonal cross-sections in [38–41], under axial, lateral, and oblique loading conditions, though the resulting structures were not compared with SFE models or physical tests or evaluated for manufacturability.

While research into multi-cell cross-sections progressed, Abbasi and Reddy investigated higher-order single-cell structures in [42,43]. These works compared the performance of square, hexagonal, octagonal, and a newly introduced twelve-edge cross-section through SFE modeling, numerical simulation, and physical testing. Furthermore, the reliance of the stability of the buckling mode on corner angle was investigated, and bounds for stability were defined based on numerical simulation. Generally, single-cell cross-sections with more corners tend to perform better [44], and the twelve-edge cross-section reflected that result by out-performing other tested single-cell cross-sections with fewer corners. The twelve-edge cross-section was further studied by Sun in [45], under the name "criss-cross configuration", where further parametric studies were performed and the effect of rounding corners with spline curves was explored. In these works, the twelve-edge cross-section buckling mode was found to be strongly influenced by corner geometry.

This work proposes a new cross-section synthesizing the findings from Abbasi and Reddy [42,43] as well as the numerous works on optimal five-cell cross-sections [18,27,31,32,36,40] by introducing a five-cell multi-corner cross-section that adds four connecting webs to the twelve-edge cross-section investigated by Abbasi and Reddy. This new cross-section is compared to a previously studied nine-cell square cross-section that was principally investigated by Zhang and others [14,17,18,36,39], as well as a four-cell model that has been studied in numerous works on multi-cell geometry [17,28,31,33]. These three cross-sections are analyzed using a combined approach for modeling through Super Folding Element theory and LS-DYNA. Additional investigations into the "criss-cross" corner element SFE model are made, given the preliminary work in [18], and shown to have reasonable accuracy compared to the LS-DYNA models. Physical testing of the four-cell cross-section is performed to establish baseline confidence in LS-DYNA simulation environment.

The four-cell, nine-cell, and five-cell cross-sections of interest are analyzed through a parametric sensitivity study and evaluation of the SFE model, with the goal of distinguishing high-performing cross-sections. Identifying the buckling mode in the sensitivity study in LS-DYNA was critical, given that the performance parameters change monotonically with variation in geometry and high-performing cross-sections are found at the boundary of the stable buckling region, rather than on the interior of the design space. Through the parametric sensitivity study, the buckling mode transition point from stable progressive collapse to global bending [46] was used in this way as a key limiting parameter, given that energy-absorbing performance decreases drastically after this transition point. Notably, this transition point cannot be predicted for multi-cell structures using SFE models, and is generally demonstrated using simulation or physical testing, such as that done by Abramowicz and Jones in [47] for square and circular steel columns. In this study, the buckling transition point was mapped and defined for all cross-sections of interest, providing an upper-bound on potential geometries. Manufacturing, as stated previously, is a further limitation upon the potential design space, and provided a lower bound for some parameters, such as thickness of the cross-section. With the design space appropriately bounded, comparison of performance within the regime of stable progressive buckling became possible. Thus, the four-cell, nine-cell, and five-cell cross-sections were compared in order to determine the highest performing structure based on current standard metrics within the field, such as crush force efficiency (*CFE*) and specific energy absorption (*SEA*).

Finally, in order to prepare these structures for practical application in automotive industry, a further refinement study was performed based on mean crush force. Given that automotive structural frames are designed to undergo a targeted mean crush force depending on their