Abstract

Human activity in engineering is dated back to antiquity. The achievements in this field of science directly contributed to the immensely far-reaching civilizational development. Nowadays, the expansion of technology is focused on advanced solutions in the aspect of designing structures to enhance their broadly defined properties.

The primary determinant in structural design is undoubtedly the load-carrying capacity, ensuring safe operation and preventing economically undesired underutilization of a mechanical system. It is necessary to provide specific methods or tools to give insight into their mechanical behaviour to address this issue. The presented work is devoted to the analysis and optimization of stress distribution in complex shell structures. Those serve as structural members of numerous relevant structures in the industry. The provided considerations are narrowed to problems of cylindrical pressure vessels; however, a similar methodology can be adapted to nearly any linear shell problem. Analytical, semi-analytical, numerical and experimental studies are considered to expand the knowledge and propose improvements to the investigated topic.

The first phase of the study is based on the theories and methods available in the literature. The stress and deformations in the cylindrical pressure vessel with standard ellipsoidal and torispherical dished ends are analyzed using membrane theory (MT) and the edge effect theory (EET). Two formulations of the EET are discussed, applied, and compared. The derivation is provided for the linear, orthotropic material model. The obtained results show that the superposition of MT and EET can result in unsatisfactory results due to simplifications in MT and neglection of the effect of surface loads on bending.

The same structures were investigated in a semi-analytical manner using the Ritz method in a subsequent study. The elastic strain energy and the work of the external forces were described according to linear shell theory. The functions describing displacements in the Ritz method are in the form of polynomials, trigonometric series, and functions similar to those derived from EET. The influence of the degree of these functions on the obtained results was taken into account. The achieved outcome agrees with the finite element method (FEM) for a relatively large range of thicknesses, proven by almost identical values of stress, displacements and strain energy.

In the conducted analyses of cylindrical pressure vessels, attention was drawn to the unfavourable stress distribution. Their maximum values in standard dished ends significantly exceed the stress in cylindrical shells, making them unsatisfactory solutions. Significant edge loads in the junctions of shell segments cause such an issue, leading to the appearance of significant bending phenomena. The shapes of dished ends described by three analytical curves, i.e. Cassini and Booth's oval and generalized clothoid, were formulated in further analyses. Specific conditions were defined to diminish the edge effect. They led to the intended effect of improving the stress distribution in the junction area but caused its maximum value to be shifted beyond this region. Therefore, the proposed shapes of shells do not constitute a significant advancement compared to the standard solutions, although their analysis provided important conclusions for further research.

The ability to carry relatively high loads by shell structures comes from their geometrical form. It is necessary to refer to optimization methods to seek the desired improvements in stress distribution. It comes from general reasoning that choosing some arbitrary geometries from an infinite set of possible solutions usually leads to poor results. In this work, the optimization is carried out in two separate processes. A parametric curve is developed to describe the shape of the dished end. Initially, the fitness function is evaluated according to MT, and the deterministic algorithm performs the optimization procedure. Due to the simplified nature of MT, the approach is then modified. The fitness function is calculated using the FEM, and the optimization is carried out by a genetic algorithm (GA). The obtained enhancement in the stress distribution is compelling while maintaining manufacturability and standard general dimensions.

Finally, the optimization results are verified in an experimental study. The pressure vessel with the optimized dished end is manufactured using Multi Jet Fusion – a 3D printing technology. Optical scanner measurements are conducted to verify geometrical deviations and to recreate the CAD model of the imperfect shape. Such a geometry is then considered in the FEM analysis. Ultimately the structure is tested on a designed test bench, enabling pressurizing of the vessel. The strain gauge measurements are performed to evaluate the stress distribution. The results are then compared for ideal and imperfect geometry by the FEM and juxtaposed with the experimental study. A good agreement is achieved, confirming the advantageous characteristics of the developed dished ends.