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Topology Optimization of Free Form Stiffener Built by Cold Spray Additive Manufacturing

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Cold Spray Additive Manufacturing (CSAM) is a solid-state AM process using kinetic energy to deposit powder particles onto the target surface. Metal deposits built by CSAM possess superior features, including no phase transition, low porosity, low residual stress, good wear resistance, high and tunable dislocation densities, and nano-sized grain structure. One of the CSAM's merits is that a large-scale part can be built on the existing structures with ease and at a high build rate, making it an attractive application for building stiffener structures on thin-walled aerospace panels. A topology optimization framework is proposed to design the free form and fabricable stiffener structures, considering CSAM manufacturing constraints, such as tool path planning, tool accessibility, stiffener cross-section geometry, and residual stress. The design and fabrication workflow is established, and the framework is validated with experiments on the topologically optimized stiffeners and the benchmark designs of grid stiffener structures.

1. Introduction

Due to the high load carrying capacity and lightweight properties, shell-type or panel-type structures have been widely used in maritime, aerospace, and civil structures. However, the thin-walled features make these types of structures sensitive to the loads leading to out-of-plane deflections, imperfections, vibration, and buckling. Adding stiffeners is one of the most popular and effective ways to enhance loading capacity meanwhile satisfy the weight requirements. Effectively adding stiffeners needs two key ingredients: (a) the design of the stiffener structures and (b) the manufacturability.

Topology optimization is a powerful design tool to find the optimal material distribution to achieve the design objectives and satisfy the design and manufacturing constraints. The topologically optimized material distribution or layout of the stiffeners can use the material mass most effectively, however, usually leading to delicate structures with very complex geometries. It brings about challenges in stiffener fabrication using the traditional manufacturing processes such as welding and machining. Recently, the fast-growing additive manufacturing (AM) technologies have eliminated such constraints and disadvantages of the traditional manufacturing processes, leading to a more flexible and effective way to build stiffeners. The birth of the AM makes it possible to build delicate structures with complex geometries generated by topology optimization.

Cold Spray Additive Manufacturing (CSAM) is a unique solid-state additive process. CSAM uses pressurized and pre-heated gas to accelerate the metal particles with a diameter of about $10\mu m$ up to about $100\mu m$ through a convergent-divergent nozzle. The particles can achieve velocities of 300m/s to more than 1000m/s. After high-velocity impact events between particles and the targets, a deposition will be formed. The deposition in CSAM occurs with a remarkably high deposition volume rate, more than 1 or 2 magnitudes higher than the powder-bed-based AM processes. CSAM can be categorized into two types: (a) Low-Pressure Cold Spray (LP-CS) usually uses air as the process gas for depositing relatively soft materials (e.g., Cu and Al); (b) High-Pressure Cold Spray (HP-CS) uses the Nitrogen/Helium gas with the pressure up to 6MPa and pre-heated temperature up to 1000 $°C$ for depositing almost all kinds of metals. Compared with the other AM processes, metal materials built by CSAM possess superior features, including no phase transition, negligible oxidation, low porosity, low-level residual stresses, good wear resistance, tuneable microstructures, good bonding strength and structural strength, outstanding radiation damage tolerance, atomic oxidation tolerance (Zou 2021; Yeom and Sridharan 2021; Yin et al. 2018; Sova et al. 2013). Due to its merits, CSAM has been widely used in various industry sectors, such as aerospace, marine & offshore, oil & gas, land transport, healthcare, defence, space technology, civil engineering, and energy. CSAM can deposit similar/dissimilar materials with a complex surface geometry on existing structures. This nature also enables CSAM to build the materials in meters of length scale without difficulty.

In the present study, the workflow of design-fabrication of free-form stiffeners built by CSAM is established, including the topology optimization method, stiffener geometry generation for fabrication, CSAM toolpath planning, and fabrication. The present study focuses on building Al6061 stiffeners on Al6061-T6 flat panels to validate the whole workflow.

2. Workflow of design and fabrication of CSAM-built stiffener

As illustrated in Figure 1, the workflow established in this study includes design and optimization, toolpath planning, fabrication by CSAM, and experimental test and verification.

The design and optimization tool is developed based on the commercial software package of ABAQUS and TOSCA 2022. The Finite Element Method (FEM) is employed to simulate the structural responses. The topology optimization method based on the Solid Isotropic Material with Penalization (SIMP) method (Bendsøe and Sigmund 2003) is employed to generate the optimal material distribution of the stiffener materials under the objective function, design constraints, and volume constraints. The design constraints in the stiffener topology optimization mainly consider the manufacturing constraints of the CSAM process, such as stiffener cross-section shape influenced by the material-dependent deposition profile and minimum distance between stiffeners determined by the CSAM nozzle accessibility. The design and optimization steps result in an STL format of the optimized stiffener.

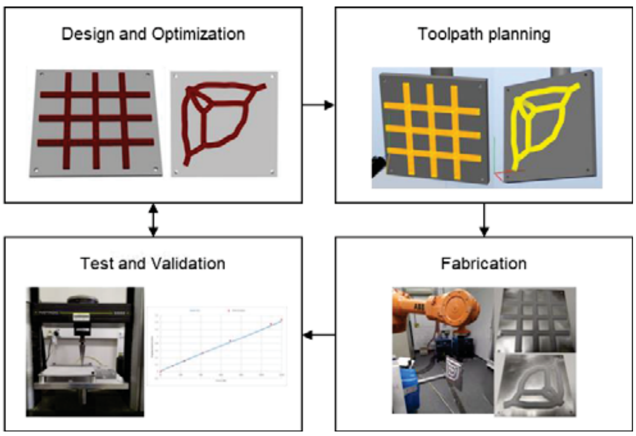

Figure 1 Schematic workflow of the design and fabrication of CSAM-built stiffener on panel-type structure

A dedicated algorithm was developed to generate continuous robotic toolpaths to fabricate the optimized stiffeners automatically. The algorithm takes the STL model of a stiffener as the input and slices it planarly to obtain polygons. Each polygon is filled by connecting all parallel contours obtained by offsetting its outer and hole contours. The toolpath planning algorithm results in a list of connected points the robot should follow to fabricate the design.

The optimized toolpath is provided to the CSAM facility with the optimized material-dependent CSAM process conditions, including the gas type, gas pressure, and gas pre-heated temperature. The CSAM process used in the current study also considers the pre-process heat treatment of the powder to improve the deposition efficiency, as-deposited part strength and ductility, and bonding strength. The traverse speed and the standoff distance from the substrate to the nozzle were empirically set up to obtain the best spray performance.

After the fabrication of the stiffener structures by CSAM, a series of experiments were carried out to verify the performance of the structures. The experimental data were compared with simulation results for calibration and validation of the design tool.

The details of the topology optimization method and procedure, toolpath planning, and CSAM process conditions are not reported in the present paper due to the length limit.

3. Topology Optimization Problem

A stiffener topology optimization problem is proposed in this section to validate the whole workflow presented in Section 2. This study's design and experiment focused on the linear elasticity regime. As illustrated in Figure 2(a), the Al6061 stiffeners are built on one side of a thin flat Al6061-T6 panel.

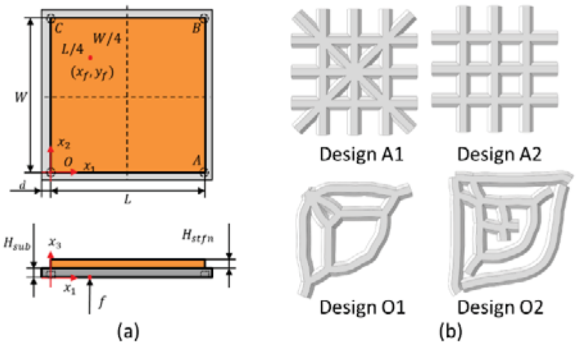

Figure 2 (a) Geometry of the panel and design domain for stiffener; (b) top view of 4 designs. Design A1 and A2 are grid-type stiffener structures for benchmarking. Design O1 and O2 are stiffeners achieved by topology optimization with different mass constraints.

The topology optimization problem can be defined by the general description in Eq.(1).

$$\begin{aligned} &\min_{\varphi} \quad max(\boldsymbol{u}) \\ s.t.\quad &Equilibrium\ equation\colon \boldsymbol{K}(\varphi)\boldsymbol{u} = \boldsymbol{T} \\ &Volume\ constraints\colon \int_{\Omega} \varphi d\Omega \le \alpha_{vol} V_{total} \\ &CSAM\ manufacturing\ constraints \end{aligned} \quad (1)$$

Here, $\boldsymbol{u}$ is the displacement, φ ($0<\varphi\le1$) is the material density function, α_{vol} is the admissible volume constraint ratio of the total volume of the design domain V_{total}, $\boldsymbol{K}(\varphi)$ is the stiffness matrix, and $\boldsymbol{T}$ is the right-hand side of the equilibrium equation resulting from the loading and boundary conditions. The manufacturing constraints considered in the present study are given by the CSAM-built cross-section geometry of the stiffener, which is a trapezoid shape with 5mm height, 10mm top width, and 20mm bottom width. The minimum distance between two neighbouring stiffener members is 10mm. The substrate panel geometry is given by 200mm×200mm×3mm. The material is avoided from being deposited in the grey colour region with a distance d=10mm to the panel edge. The stiffener design domain is defined by L=180mm, W=180mm. The walls of 4 holes O, A, B, C with a diameter of 6mm are fixed. A concentrated force f=1.2kN is applied at the point (x_f, y_f) on the bottom surface of the substrate panel, where $x_f = L/4,\ y_f = 3W/4$. The optimized stiffener structures are generated using different volume constraint α_{vol}= 10%, 15%, 20%, 27%, 35%, 40%, 48%.

4. Resutls and discussions

Two grid-type stiffener designs shown in Figure 2(b), Design A1 and Design A2, are proposed to compare the performance of the optimal and non-optimal designs. Two topologically optimized stiffeners, Design O1 and Design O2, are selected for CSAM fabrication shown in Figure 2(b).

The designed volume ratios are $\alpha_{vol} = 57\%$ for Design A1, 30% for Design A2, 30% for Design O1 and 48% for Design O2. Designs A2, O1 and O3 are fabricated by CSAM, and the fabricated structures are shown in

Figure 3. The mass of the fabricated stiffeners is 183g, 130g, and 196g for Design A2, O1, and O2, respectively. The discrepancy between the designed and fabricated mass results from the precision limitation of the CSAM process.

Figure 3 CSAM-built Al6061 stiffeners on Al6061-T6 panel

The simulated maximum deflection of topologically optimized designs (TO Designs) with volume constraint ratios of 10%, 15%, 20%, 27%, 35% 40% are plotted by black dots in Figure 4, and these data are used to generate a fitting curve defined by the function ($y = 5.274e^{-0.01x}$). It is noted that the fitting function does not use the data points of Design O1 ($\alpha_{vol} = 30\%$) and O2 ($\alpha_{vol} = 48\%$). However, the fitting function can predict the deflections of these two designs very well if the same optimization strategy is employed.

After fabrications, experiments were conducted to examine the maximum deflection under 1.2kN concentrated forces. The loading condition and boundary conditions are described in Figure 2. Virtual tests on the structures with different designs are performed, following the experiment set-ups on loading and boundary conditions. The experimental test data of the fabricated designs are given in Figure 4 and Figure 5. The comparisons present good agreement between simulation results and experimental measurements, thus validating the design and fabrication workflow.

Figure 4 demonstrates the effectiveness of the topological optimization by comparing the optimal and non-optimal designs. The mass of Design A2 and Design O2 are similar; however, under the same loading condition, Design O2's stiffness is significantly improved, leading to about a 50% reduction of the maximum deflection. Comparing Design A2 and Design O1, one can find that using much less material mass, the topologically optimized stiffener structures can achieve similar overall structural stiffness, which can also be observed by comparing Design A1 and Design O2.

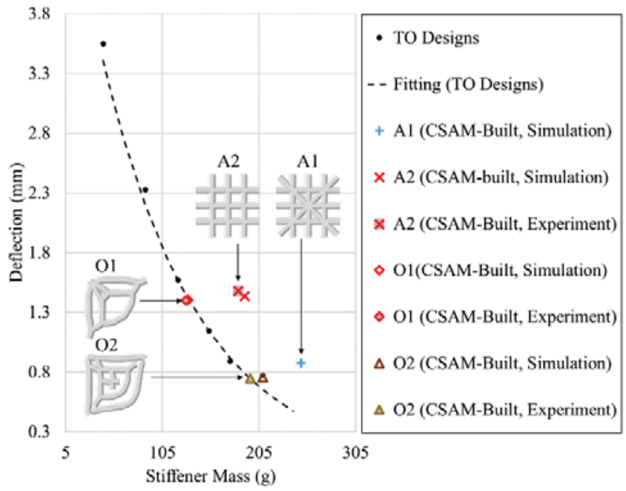

Figure 4 Comparisons of simulation and experiment data of maximum displacement of the optimized and benchmark designs

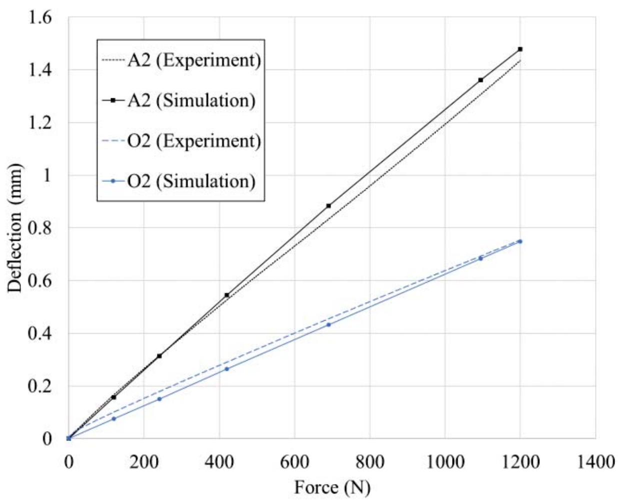

Figure 5 Comparisons of simulation and experiment data of deflection vs. force.

5. Conclusion

This study established and validated a workflow of design, optimization, toolpath planning, fabrication, and verification of the CSAM-built free-form stiffener structures. The design and optimization tool can generate fabricable stiffener designs, including grid-type and topologically optimized free-form stiffeners. The design and optimization consider the real-world CSAM manufacturing constraints to make the design fabricable by CSAM. Following the optimal toolpath planning strategy, the design can be realized by CSAM using the optimal process conditions with ease. The verification experiments have been well defined to provide reliable validation data. The workflow has been successfully validated by the good agreement between the experimental data and simulation results. Future works will expand this workflow into designing and building the stiffener structures on three-dimensional curved shell-type thin-walled structures.

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