Contributions to the Analysis and Characterisation of Mechanical Structures through Numerical and Experimental Methods: Applications to Hydraulic Turbines and 3D-Printed Polymeric Components

Habilitation Thesis
Abstract

Dr.Eng. Vasile COJOCARU

2026

ABSTRACT

The habilitation thesis entitled **"Contributions to the Analysis and Characterisation of Mechanical Structures through Numerical and Experimental Methods: Applications to Hydraulic Turbines and 3D-Printed Polymeric Components"** summarises the scientific, professional and academic work carried out since the award of the PhD degree in Mechanical Engineering (2013). The research presented is situated within the fields of strength of materials, the analysis of complex mechanical structures, numerical simulation using the finite element method, and the experimental characterisation of materials and mechanical components.

Chapter 1. Scientific, professional and academic achievements

Chapter 1 presents the main results obtained through research, grouped into two major areas. The first area focuses on the analysis of stress states, deformation behaviour and durability of critical components of hydraulic turbines. The second area focuses on the mechanical characterisation of polymer components produced by additive manufacturing, with an emphasis on the influence of process parameters on the dimensional accuracy, mechanical strength, tribological behaviour and anisotropy of 3D-printed structures.

Numerical and experimental analysis of hydraulic turbine components

The first research area was developed in close connection with the requirements of the hydropower industry, particularly the issues associated with the operation, modernisation and extension of the service life of hydropower equipment. Hydraulic turbines comprise components with complex geometries, subjected to variable mechanical stresses, transient operating regimes and severe operating conditions, which necessitates a rigorous assessment of stress states and fatigue behaviour.

Within this research area, components such as the runner hub, the servomotor piston and the runner cover of a six-blade Kaplan turbine, and the spiral casing of a Francis turbine were analysed. The studies aimed to identify critical areas, determine the von Mises equivalent stress distributions, evaluate displacements and estimate fatigue behaviour. The methodology included 3D modelling, the definition of actual loading conditions, the application of constraints, finite element discretisation, convergence analysis and the interpretation of stress and displacement distributions.

For the Kaplan turbine runner hub, the analysis was performed under representative operating conditions, considering the combined effects of hydrodynamic loads acting on the runner blades, mass and centrifugal forces, as well as the forces generated by the blade positioning

mechanism. Both normal operating regimes and transient conditions associated with pressure surges were considered. A significant contribution was the determination of the reaction forces transmitted through the hub bearings and their integration into the numerical model using sinusoidal distributions, which provide a more accurate approximation of the actual load transfer mechanisms. The results showed that the most critical stress areas are located near the main hub bearings, where the interaction between the blade, trunnion and actuation mechanism leads to pronounced stress concentrations. The fatigue assessment highlighted the importance of complementing numerical simulations with experimental determination of material-specific fatigue behaviour under representative service conditions.

For the servomotor piston, the analysis considered the load cases corresponding to the maximum pressure acting on the upper or lower active surfaces of the piston. The results indicated that, under the adopted modelling assumptions, the component has an adequate strength reserve, confirming the structural validity of the proposed design.

In the case of the runner cover, the numerical investigation was carried out on the hub-runner cover assembly, considering the effects of hydraulic pressure, the reaction forces transmitted through the hub bearings and the pretension forces in the threaded joints. The analysis revealed that the highest stress levels occur in the flange and connection regions of the runner cover, where load transfer and geometric discontinuities favour local stress concentrations. These results highlight the need for a careful assessment of the joint areas, particularly regarding cyclic loading and long-term structural integrity.

For the spiral casing of a Francis turbine, the analysis was conducted for both normal operating conditions and transient regimes associated with shutdowns and load rejection. The numerical model included the internal pressure acting on the flow path, the forces applied at the end sections, the self-weight of the structure and the loads transmitted through the guide vane assembly. The results showed that the most highly stressed regions are located at the connections between the stay vanes and stay ring, where the structural geometry and the load transmission path generate significant stress concentrations. The analysis also highlighted the significant influence of transient operating regimes on the stress and displacement fields, emphasising the need to evaluate fatigue durability in complex hydropower structures.

The fatigue analysis of the spiral casing required consideration of the specific characteristics of the materials used, including cast and welded steels, for which fatigue data are often limited, scattered or strongly dependent on manufacturing and service conditions. The use of equivalent material data and information available in the literature made it possible to estimate the fatigue behaviour under conservative assumptions. The results emphasised that the operating environment, surface condition, component size and fatigue correction factors may substantially reduce the effective fatigue strength. Consequently, the estimation of service life should be based on a conservative methodology, correlated with actual operating data, monitoring activities and periodic inspections.

Overall, the research dedicated to hydropower equipment demonstrates the usefulness of numerical methods in assessing the stress state, identifying critical regions and estimating the structural safety of components operating under complex loading conditions. These investigations provide useful scientific and technical support for design, refurbishment, predictive maintenance and service life extension of hydroelectric equipment. The practical relevance of the contributions is further supported by the fact that a significant part of the research was carried out in collaboration with industrial beneficiaries, allowing the proposed methodologies to be applied and validated in engineering contexts close to real operating conditions.

Characterisation of polymer components produced by additive manufacturing

The second area of research concerns the analysis of the mechanical properties of components produced by additive manufacturing, using Fused Filament Fabrication (FFF) technology. The use of 3D-printed parts in technical applications requires a detailed understanding of the influence of process parameters on mechanical behaviour, dimensional accuracy and the stability of physical and mechanical properties. A review of the literature shows that parts produced by FFF cannot be considered homogeneous and isotropic. The layer-by-layer deposition process results in the emergence of anisotropy, areas of interlayer adhesion and significant sensitivity to variations in process conditions.

The investigation of printing temperature showed that it influences both dimensional accuracy and tensile strength. Temperatures that are too low can lead to insufficient interlayer adhesion and delamination, whilst temperatures that are too high can cause over-extrusion, dimensional variations and changes in material flow, cooling behaviour and interlayer bonding. For the analysed PLA specimens, optimal printing temperature ranges were identified, which also depended on the filament colour. This result highlights the fact that colour additives can alter the thermal and mechanical properties of the filament.

The influence of layer height was also significant. Thinner layers generally contribute to better dimensional accuracy and a more uniform surface, but can affect printing time and the cooling behaviour of the material. Maximum tensile strength is influenced by the interaction between layer height, printing temperature and the quality of interlayer adhesion. Consequently, process optimisation cannot be achieved by modifying a single parameter, requiring a correlated analysis of the entire set of process conditions.

The investigation of high printing speeds showed that the deposition speed has a direct influence on mechanical strength. Under certain experimental conditions, a speed of approximately 300 mm/s resulted in high tensile strength, whilst higher speeds led to a decline in mechanical performance due to over-extrusion, non-uniform deposition and reduced interlayer adhesion. The results indicate that increasing printing speed may improve productivity, but this benefit must be balanced against the potential reduction in mechanical performance.

A key finding of the research is that filament colour significantly influences the properties of printed parts. Although the base material may be the same, the additives used for colouring can alter the thermal properties, material flow, cooling behaviour and mechanical properties of the parts. The differences in tensile strength between test specimens made from filaments of different colours were significant, confirming the need to characterise each material used in engineering applications, not just the generic type of polymer.

The printing configuration, namely printing a single specimen or multiple specimens simultaneously, influenced the mechanical behaviour by altering the local thermal conditions. Printing multiple specimens simultaneously alters the cooling time between layers, the local temperature and the uniformity of the thermal field, which can lead to variations in tensile strength. The results showed that the position on the build plate and the number of specimens printed simultaneously can influence the values of the mechanical properties.

A significant part of the research was focused on cellular structures produced by additive manufacturing. These structures enable weight reduction, material savings and the adjustment of stiffness or strength to the requirements of the application. The bending behaviour was analysed for specimens with hexagonal, triangular and grid infill patterns. The results highlighted significant differences between the structures, both in terms of stiffness and sensitivity to the direction of the applied force. The hexagonal and triangular structures exhibited lower deformations and more stable behaviour with respect to variations in the direction of the applied force. In contrast, the grid-type structure exhibited significantly greater displacements for the same material consumption, indicating lower stiffness under certain loading conditions. A comparison of the experimental results with those obtained through FEM analysis showed good agreement, confirming the potential for using numerical simulations to optimise 3D-printed cellular structures.

The anisotropic nature of 3D-printed structures is one of the key findings of this line of research. The mechanical properties vary depending on the printing orientation, the direction of loading and the internal architecture of the component. This behaviour must be considered from the design stage, as an inappropriate build orientation or infill pattern may reduce strength and accelerate failure.

Summary of scientific and professional achievements

The scientific and professional activity is reflected in 86 papers indexed in international databases, including 25 papers indexed in Web of Science, 9 published in Q1 and Q2 journals. The visibility of the research is reflected by 360 citations in Web of Science (excluding self-citations). The academic activity is complemented by the publication of four books.

In the field of applied research and technology transfer, seven research and development contracts have been coordinated as project leader, in addition to eleven contracts carried out as a member of the research team. Managerial experience is also demonstrated by the coordination of two development projects funded by non-refundable grants, as well as by participation as a member of eleven projects.

Chapter 2. Career evolution and development plans

Chapter 2 outlines future directions for scientific, professional and academic development. In the field of hydropower, research will focus on extending studies on the fatigue behaviour of critical components, determining the actual fatigue curves for the materials used in service, monitoring operating regimes and developing unified analysis models for reaction hydraulic turbines.

In the field of additive manufacturing, future research will focus on the characterisation of the anisotropy of cellular structures, the optimisation of process parameters, the analysis of polymer composites, and the development of predictive models for the mechanical properties of 3D-printed components. These areas of research will enable the design of lightweight components with controlled properties and mechanical behaviour tailored to the requirements of engineering applications.

By combining numerical simulations, analytical calculations and experimental tests, future research will contribute to advancing knowledge in mechanical engineering and to solving specific industrial problems. The results obtained provide a basis for the development of PhD research topics and the expansion of inter-university collaborations and partnerships with industry.