Experimental Investigation of Beams under Coupled Bending and Torsion

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Experimental investigation of beams under coupled bending and torsion

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Abstract

The design of doubly-curved systems called for innovative modelling techniques to evaluate the final geometry of the structure. They can simulate the behaviour of beams under large displacements. Even though it is never analysed, the deformation path is can be critical in such complex configurations. This paper analyses the potential of digital technologies to investigate the behaviour of beams under bending-torsion coupling in large deformation. In a first part, we will present the setup for an experiment, based on the use of robotic arms. The versatility of robotic arms allows to access complex configurations or loading paths, while controlling the test either in displacements or in forces. In a second part, an enhanced photogrammetry procedure is introduced. The aim is to retrieve the geometry of the beam even in the case of complex 3D shapes. The acquisition yields a point cloud representation of the beam. Finally, we propose a workflow to make the interaction with robotic arm, simple and efficient. The novel experimental setup aims at making possible the study of beams with complex form, under ever more complex force.

Keywords: Large Deformation, Robotic, Photogrammetry,

1. Introduction

Active-bending structures are a family of systems built from elastically deformed rods. For example, an elastic gridshell is made of continuous bars assembled on the ground to form a grid. This initial grid is then bent to a target shape and braced to fix the geometry. In the last few decades, active-bending systems have become very popular for their capacity to develop complex doubly-curved shapes. They can be found in various context, from temporary doubly-curved roof structures [1], to structural demonstrators with an innovative use of materials [2], and art pieces where elastically bent bars interact with tensile membranes [3].

The common factor in active-bending structures is the large deformation of its members responsible for the stiffness of the final form. In their deformed configuration, the beams are subject to all kind off stresses, essentially bending, but also torsion due to couplings effects and to connections between them [4]. It induces a pre-stress state in the structure. Therefore, it is necessary to account for the material properties in the design and form-finding process of a bending-active structure. In order to allow for large deformation of the beam, the material must have high elastic strain and a high limit stress. Yet, leaving aside the strength requirements of these structures, the mechanical properties also impacts the stable shape. The curvature of a beam depends on its bending stiffness. The interdependence of form, force and materiality is very strong in active-bending structures which calls for a thorough understanding of the behaviour of beams.

Many recent researches have been led on how to model these structures and get the geometry in static equilibrium. Common algorithms tend to have heavy convergence problems due to the large rotations and displacements, and can become very expensive in terms of computational time. A very popular method to form-find these structures is the dynamic relaxation method combined with the use of a discrete element model. Since the 3 degree-of-freedom element proposed by Adriaenssens et al. [5], more complete formulations have been proposed [4],[6][7],[8]. The aim is to model as best as possible the structural behaviour of the beams and of the connections to obtain a precise evaluation of the final shape. However, in these methods, very little attention is given on the actual erection process. During this phase, the members are subject to complex deformation paths which are the origin of strong non-linearity and potential instability [9]. For such deformations, it is necessary to account for second order effect, like beam-length variation.

The accuracy of the different formulations is only being tested through the design of pavilions. Experimentally, little has been done to study the behaviour of beams under large deformations following complex deformation paths. The lack of experimental results in this domain can be explained by two reasons. On the one hand, the principal difficulty is to prescribe 3D deformation paths. Commonly, experimental setups are able to work in-plane, using either an imposed force or displacement. They often focus on evaluating the characteristic for one stress only, leaving aside any coupling effects. Therefore, they are not able to replicate the peculiar situations found in active bending structures. On the other hand, to get a hold of the beam behaviour, one wants to have access to the displacements in the deformed configuration. To measure displacements along one axis, tools like linear variable differential transformers (LVDT) or laser sensors are capable of very precise assessment. When it comes to 3D deformations, contactless measurement techniques are preferred. A popular method is digital image correlation (DIC). However, for large deformations, large decorrelation between images occurs, preventing the algorithm from evaluating the displacements properly. Acquiring the geometry of a deformed beam is a complex matter in the case of large displacements because of the wide range of shapes accessible. Thus, even though the theoretical backgrounds of the proposed discrete element formulations are reliable – e.g. Saint-Venant, Kirchhoff – few experiments have assessed the models.

This paper analyses the potential of digital and robotics technologies to investigate the behaviour of beams under bending-torsion couplings and large deformations. In a first part, a robotic control of the experiment will be examined. The positioning flexibility and accuracy is placed at the service of the experiment. In a second part, an improved photogrammetry procedure is presented for a full-field geometry measurement of a 3D deformed beam. Finally, a software solution is presented to overcome the difficulties introduced by the use of robotic arms.

2. A robotized experiment

As for the experiment, it is typically desired to examine the behaviour of a single slender beam by imposing conditions at its ends, either in displacements or in force. With these conditions, already a vast number of problems and configurations can be tested.

2.1. Motivation

Previously, we have seen that complex deformation paths could not be followed with the currently available setup. To allow for such experiments, we propose to introduce robotic arms in the process. Several reasons motivate this choice:

- Accuracy: A robotic arm is controlled by a series of servomotors. A feedback of the angular position of each of the axis of the robot is available thanks to rotatory encoders. This system gives industrial robots the capacity to position any tool fixed at its end with a submillimetre precision. In the case of the ABB IRB120, the positioning accuracy is about 0.02 mm, when the orientation precision is about 0.005° on each axis. This experimental measure was evaluated with a weight of 1.1kg at the arm end. It is important to understand that when several positions are prescribed, there isn't any propagation of the error on the position. Each target of the robot is calculated with respect to the robot coordinate system and not to the previous position.

- Automation: The motion of an industrial robot is controlled via programming. One solution is to give a set of successive positions to be reached, called targets, while specifying the type of movement to be achieved in-between. Another way, is to provide a curve, called the path, to be followed by the end of the robotic arm. The automation of the movement comes as a benefit, and not as a constraint. Firstly, the experiment can be conducted without much supervision and intervention. More importantly, once the path of the tool is defined, the experiment can be repeated easily by relaunching the program.
- Flexibility: A 6 axis robotic arm gives access to many positions. Each axis has a range of movement of at least 180°. Thus, the limiting factor of these robots is their reach. In addition to the position, the speed and the acceleration of the motion can be dictated or bounded.
- Adaptability: The robot has the capacity to host various tools, as long as it can be wired up to the wrist of the robot. For example, in the last few years, many companies and laboratories have been starting to pour concrete using robots [10]. The ITKE in Stuttgart has been building several pavilions using robotic fabrication. In [11], timber beams of a reciprocal structure were robotically manufactured using a milling head on a 6-axis robotic. Recently, [12] used a laser doppler vibrometer fixed on an industrial robot to perform full-field velocity measurements.

2.2. Principle of robotic monitoring of complex path

For the purpose of large deformation experiments, the versatility in position and in use of 6 axis robotic arms can be used to perform complex path using an adapted tool to hold one end of the beam, with the other fixed in place. During such experiment, the beam is deformed progressively by either controlling the displacements along a programmed path or by dictating the force applied. Thanks to the rotatory encoders it is possible to get a precise estimation of the position of the robot's wrist.

However, by default, there is no force measurement embedded in the robot. To have an evaluation of the stress, a force sensor has been installed at the end of the robotic arm. Fixed on large 6-axis robots (ABB IRB6620), the force sensor is able to measure forces up to 1500 N applied in any direction with a precision of 0.5N, and to measure all three moments up to 240 N.m with a precision of 0.1 N.m. The force sensor is also connected to the robot's motion controllers, enabling the control of the robot according to the measured force and to cancel the effect of the sensor's weight when the force is monitored.

Thus, with the force sensor coupled to the robot, we are able to dictate the position while measuring the force, or apply a given force while monitoring the position of the tool. With this robotic setup, a great variety of new tests can be conducted, with reliable information acquisition.

2.3. Experimental validation

In order to demonstrate the validity of the described setup, we present a case study. In this experiment, we want to study the torsional buckling of a beam, which includes instability, out-of-plane deformations and large displacements. The setup involves a beam fixed at one end and loaded by a robotic arm at the other end. To foster the apparition of torsional buckling, a thin-walled bar is used and loaded in the strong bending axis. The beam is a 3-meters long steel IPE80. Because the control in force of the experiment was not yet available, for security reasons, the displacement at the end was dictated and the force monitored.

The finite element software suite Abaqus has been used to dimension the test. The aim is to find a deformation path of the beam when the load is progressively increased and to ensure that the maximal force measurable by the sensor is not reached. The mechanical modelling of beam instabilities requires the introduction of initial geometrical defects. The path and the force found with the analysis are strongly dependent on the initial imperfection. Thus, the deformation path imposed to the beams may not be the one that would have been followed with a force controlled essay. Analyses were consequently run, in order to get a post-evaluation of the initial out-of-straightness.

The initial geometrical defect was evaluated with respect to the first torsional buckling mode of the beam. The mode has been normalized in order to have a 1 mm default at the loaded end of the beam. A visual estimation of the out-of-straightness evaluates the imperfections at no more than 20 mm at the end of the beam. Thank to simulations on Abaqus, it was found that the best fitting force-displacement curve corresponded to a beam with a 40 mm default (Figure 2). Thus, even though the visual defect isn't large, the experiment allowed to identify that the beam behaved with an equivalent defect of 40 mm. Reverse engineering of equivalent imperfections for stability analysis is thus one open problem that could be addressed with this kind of robotic experiment.

Figure 1: Torsional buckling

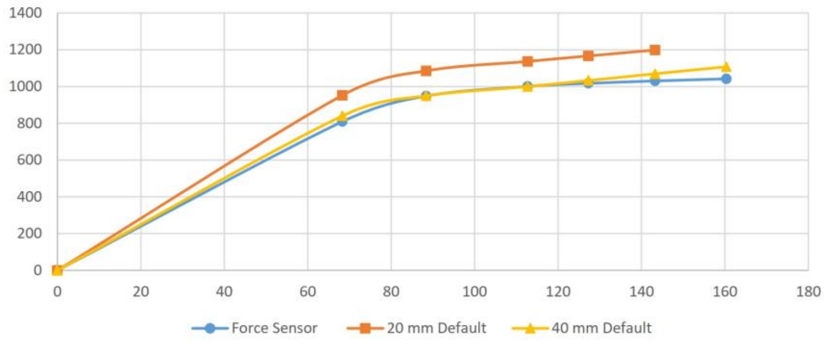

Figure 2: Force(N) - Displacement(mm) curve of the experiment and simulation

3. Robotized Photogrammetry

In the presented experiment, material properties of the tested beam can be retrieved with information on forces and displacements at one single point. However, for an increasing number of identification techniques based on the redundancy of measures, full-field displacement measurement is required. If so, additional dispositions should be used to evaluate the 3D deformed geometry.

3.1. Photogrammetry for large displacements

The measure of large out-of-plane deformation, as of 3D deformed shape in general, is complex. The most popular technique involves the digital image correlation (DIC). In this method, a fixed camera captures the motion of the beam being deformed. Having a fixed camera and tracking the beam in each image allows to evaluate the successive positions of the beam. In order to measure out-of-plane displacements at least two cameras are needed. Still, large decorrelation between images may occur when the displacement of the beam is too large, preventing the software from evaluating the actual deformation.

A popular tool, also based on numerical image correlation is photogrammetry. It refers to every measuring technique that allows to model a 3D space using only 2D images [13]. Contrarily to DIC which uses a fixed camera to capture several configurations of a moving element, photogrammetry analyses a fixed configuration of an element using a moving camera. Pictures are taken all around the studied object and a numerical 3D point cloud is produced after post treatment. Because the camera is not bound to a single position, this technique allows to rebuild almost every shape. Photogrammetry allows to accommodate the large displacements and is able to rebuild very complex configuration. The point cloud model produce after analysing the pictures yields the measure of the beam 3D displacement.

3.2. Robotic contributions to the photogrammetric process

Since the 19th century, the photogrammetric analysis process has evolved a lot thanks to the creation of dedicated tools. In the middle of the 20th century, the analysis needed a qualified personnel to be carried out and was time consuming. With the apparition of computers and thanks to their increasing calculation capacity, the photogrammetric process has been simplified and is also much more precise than what it used to be [14]. The parameters of the camera (optical settings, position and orientation in space) are found automatically thanks to feature detection algorithms [15], bundle adjustment methods (Levenberg-Marquardt) and optical distortion models (Fraser). However, some steps in the process could not be improved. Taking the pictures for the analysis is time consuming. But more importantly, the model produced at the end is in a relative scale. The point cloud model is built using pictures whose size is counted in pixels and not meters. Solutions involving GPS localisation can be found for aerial photogrammetry. For human scale acquisition, like the reconstruction of the shape of a deformed beam, more precision is needed.

The idea here, is to fix a digital camera on a robotic arm and to adapt the photogrammetric study to this setup. The flexibility of the robot is again at the service of the large deformation experiment. Thanks to the wide range of positions available to the robotic arm, pictures can be taken all around the studied object, even in case of complex shape.

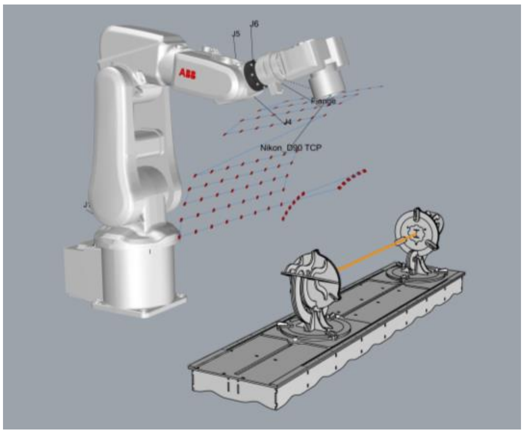

Figure 3: Simulation of the experiment

With the proposed setup, the acquisition process becomes fully automated. The robotic arm is given a list of positions and orientations from where the pictures have to be taken. The camera and the motion of the robotic arm need to be synchronized: once in position, a picture is captured then the robot moves to the next point. The coordinates from where the pictures are taken are then given as an input for the photogrammetry analysis. During the post-treatment of the images, the input positions define a scale for the 3D point cloud, in a similar way as interpreting the GPS information. Furthermore, it is possible to skip the research for the parameters of the camera, which is a delicate step of the analysis. The positioning accuracy of the robot provides the exact orientations for every pictures in space. Therefore, this setup allows for an improved and more robust procedure for the reconstruction of a scene while using photogrammetry.

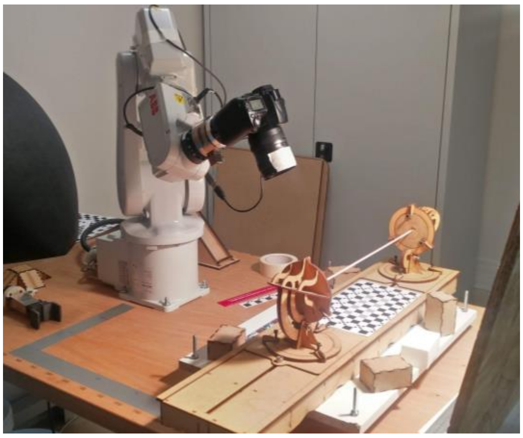

Figure 4: Robotized photogrammetry setup

3.3. Case study

In order to evaluate the proposed system, a slender element with imposed boundary conditions is studied. We want to get a full-field measurement of the position of the beam thanks to the point cloud. For practical purposes, the experiment had to be led on objects with reduced dimensions. The beam has a constant 1.5x4.5 mm cross-section and is 600mm long. It is fixed on a laser-cut support to manage the boundary condition accurately. A commercial camera is fixed at the end of an IRB120 (Figure 4).

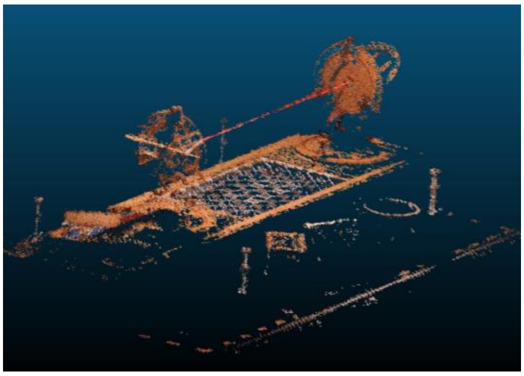

Figure 5: Point cloud of the experiment

The photogrammetry study has been conducted with MicMac, a software solution developed by the French National Institute of Geography [16]. The proposed setup allows to simplify and to speed-up the analysis. However, the quality of the point cloud (Figure 5) was not as good as expected. The beam was rebuilt with a precision of ±3 mm, which is not enough in comparison with its dimension.

It was identified that the calibration process of the camera had to be improved to get accurate results. Indeed, the information obtained from the robot is the position of its wrist, when the optical centre of the camera is required for the photogrammetric software. The orientation of the optic centre with respect to wrist of the robot corresponds to a rigid body transformation of each position. This problem of homogeneous transformation of the form AX=BX has been raised and solved in many different ways in Euclidian space or quaternions [17],[18]. For photogrammetry, a very precise calibration is needed in position and in orientation. To get such demanding accuracy, dedicated tools are necessary.

4. Workflow

In the previous sections, solutions introducing industrial robots were presented to answer the need, on the one hand to apply elaborate 3D loading paths to the beam, and on the other and to measure complex deformed geometries. However, the use of a robotic arm implies a specific workflow. To overcome this concern, a software solution has been developed. It makes use of a virtual experimental setup, upstream of the essay, to model the path and the manage the interaction with the robot.

4.1. Virtual experimental model

The use of industrial robots constrains the user to program the robotic arm ahead of the experiment. To help the user design the experiment and define the path followed by the arm, a virtual experimental setup [12] is modelled. To do so, we have chosen to work with the CAO software Rhino3D and its parametric design interface called Grasshopper3D. The aim is to create a virtual representation of the robot’s working environment (Figure 6). The model must include the geometry of different objects:

- The measuring tool, defining the spatial occupancy, as well as the lever arm between the end of the arm and the tool control point;
- The measured object, used to create targets to be reached by the tool control point;
- The robotic arm, needed to evaluate the accessibility of the targets;
- The reference objects, helping the positioning of the measured object with respect to the robot.
- The environment objects, i.e. all objects that are in the robot's reach, and can be a potential source of collision;

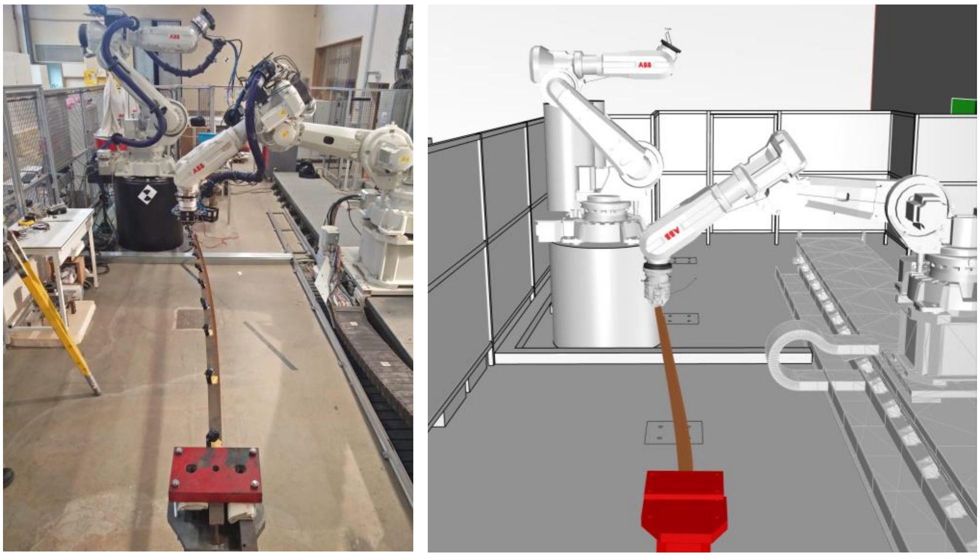

Figure 6: Virtual experimental setup

From the virtual experimental situation, the list of positions for the arm is defined. The strength of this step lies in the ability to parametrize the path in Grasshopper3D. It is possible that the wanted position, does not fit the limitations of the robotic arm. Thus, when a target cannot be reached by the robot, it will be necessary to take a step back. Therefore, the definition of the trajectory of the robots should rely on the position, the form of the measured object, and eventual other parameters. The definition of the set of points is thereby an iterative process (Figure 7).

4.2. Robot management

From the list of positions defined in the parametric software, we want to verify their accessibility and the motion of the arm in-between which is done using HAL-Robotics software. This Grasshopper3D plug-in manages and predicts the motion of the robots. It can predict whether or not the robotic arm is capable of reaching the position, and also allows to give constraints on the motion, like speed, acceleration or spatial restrictions. The whole movement of the robotic arm between the positions is simulated and previewed. Thus, thanks to the virtual experimental setup, collisions between the tool, the robot and its environment can be easily avoided.

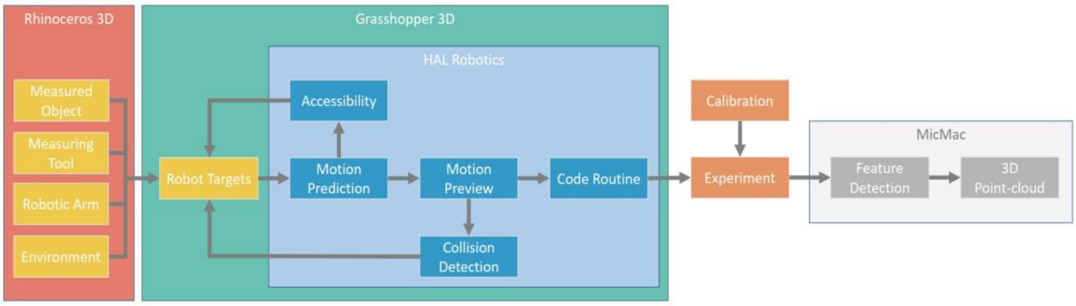

Figure 7: Proposed workflow for the design of the experiment

Once all the targets are reachable by the arm, HAL-Robotics generates the instructions for the movement of the robot in the form of a code. The code is written in a specific programming language depending on the brand of the robot used. The communication between the computer and the robot controller can be directly configured in the plug-in to export the code directly.

The combination of a coarse model of the object, of parametric design of the position in Grasshopper3D and of the simulated robotic cell using HAL Robotics, is extremely powerful. Thanks to parametric design, the object studied can be moved in space to accommodate accessibility issues and the list of positions, the analysis of the targets by HAL, and the code generation will be automatically updated. A clever parametrisation allows for a quick adaptive solutions and makes the design phase of the experiment extremely efficient.

4.3. Preparing the actual experiment.

Before running the experiment, the real setup has to be calibrated in order to match as best as possible the virtual experiment model. The measured object has to be positioned relatively to the robot, using the reference objects. For some experiment, like the robotized photogrammetry, an accurate positioning of the object is not essential, the principal requirement is for the object to be in the area of sharp focus of the camera. In many case a precise visual calibration can be sufficient. However, for procedure like the milling of a wooden object, great precision may be necessary [11].

Conclusion

This paper presents a novel and promising methodology to study the behaviour of beams under coupled bending and torsion. The introduction of industrial 6 axes robotic arm improves the range of possibilities in terms of large deformation experiments. Using only one setup, objects with a wide variety of shapes and sizes can be measured. To overcome the difficulties introduced by the uses of the robots, a software solution has been presented which rely on the use of a virtual experimental setup.

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