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STRUCTURAL ANALYSIS FOR A REDUCED SCALE MODEL OF A HYDROPOWER PLANT DEBRIS CONTAINMENT GRID

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Abstract. *Accumulation of debris in hydropower plants is an important concern to be addressed in order to avoid the reduction in the plant efficiency. This phenomenon can be mitigated by the usage of debris booms, which are floating structures installed in the river used to contain and deflect these debris. Large logs associated with the high water flow velocities are the present elements in the Madeira River, more specifically at the Santo Antônio hydropower plant. Being a non-trivial incident, the usage of experimental techniques is recommended to better understand the dynamics of the log booms and verify numerical and analytical models. This paper develops a structural analysis for a truncated 1:10 scale model of a containment structure that is towed in the model basin of the Institute for Technological Research. It presents the methodology used for design the experimental setup, the manufacturing project and test considerations of the scale model, the instrumentation adopted to measure the local strains and total forces, and the data reduction on the conduced tests. The developed methodology is part of an R & D project requested by Santo Antônio Energia and developed by IPT.*

Keywords: *Log boom; Model instrumentation; Experimental tests; Towing Tank; Data analysis*

1. INTRODUCTION

Structures and equipment designed to be installed in a river needs to consider the effects of impact and accumulation of debris present in this fluvial environment. In order to manage properly this occurrence, some mitigation techniques require the installation of non-permanent floating structures, generally known as debris booms, which have the purpose of deflecting surface debris and protecting hydrokinetic devices (Bradley, *et al*., 2005).

Santo Antônio hydropower plant, located on Madeira River, North of Brazil, is affected by the large amount of logs flowing throughout the river extension, mostly due to erosion of emergent and riparian tress. Countermeasures to avoid damages on the machinery and reduction in energy generation involve the placement of steel grid lines equipped with floaters, known as log booms, across the river, as seen in Figure 1. These structures are designed to contain and deflect wood logs and other larger debris, even the ones located below the water surface (Santo Antônio Energia, 2017).

Due to its disturbed nature and associated access difficulty, the necessity of a fully controlled experiment becomes justifiable. Several experimental tests involving debris containment structures have been performed using physical modeling. Haehnel and Daly (2002) collided woody debris with structures using flume and test basin laboratory facilities to investigate the maximum impact force that floodplain structures are exposed when hit by floating woody debris. The tests investigated the influence of collision geometry, determined by the debris impact orientation, and construction material of the model face on the maximum impact forces.

Recently, Schmocker and Hager (2013) conducted a series of systematics tests to observe the wooden debris accumulation at a basic scale model debris rack, installed in a rectangular model channel. The main purpose was to analyze various aspects regarding the modeling of wooden debris and to provide information on reducing the laboratory effort. It aimed to achieve a relation for the backwater rise and the accumulation processes and whether or not it was important to model them properly in small scale.

Recent efforts of Katsuno *et al.* (2017) and Castro *et al*. (2017) have shown the development of an instrumentation procedure and validation of numerical methodology for log containment grid scale model. The goal was to achieve qualitative results for the force pattern acting on this type of models.

Figure 1. Log containment by log boom line

Once the logs containment structures are under large stresses while in operation, this paper focuses on developing an instrumentation process for data analysis, from water proof strain gages and uniaxial load cells, of a truncated scale model. The data is generated by towing a model of log boom line in the IPT's Towing Tank and it aims to estimate the stress behavior along the structural elements by measured data treatment. The experimental procedures cover steps like model design, manufacturing, instrumentation, calibration, tests, data reduction, and further analysis. All the procedures are part of a technological R & D project developed by IPT.

2. EXPERIMENTAL METHODS

The main objective of this study was developing a structural analysis for 1:10 scale model of a log boom line tested in a towing tank. The collected data will help to understand the magnitude of forces and how the strain flow behaves in this structure. This work, jointly with field measurements, can be used to develop a correlation model to track stresses acting on the full scale prototype, in which the river conditions are not controlled and uniform. It can be used to find the critical regions where failures might occur, for example.

2.1 Facilities and Model

The Laboratory of Naval and Ocean Engineering (NAVAL) of the Institute for Technological Research (IPT) has facilities and equipment for several kinds of hydrodynamic experimental tests, including a towing tank, Figure 2, equipped with a dynamometer carriage, a planar motion mechanism (PMM) and a wave maker. Its main particulars are shown in Table 1. The log boom model was attached to the carriage and towed to simulate a scale river stream velocity.

Figure 2. IPT's Towing Tank

Table 1. IPT’s Towing Tank main particulars

Dimensions	Section	
	Narrow	Wide
Length (m)	80	200
Depth (m)	4.0	6.6
Width (m)	2.2	3.5
Carriage Maximum Velocity (m/s)	3.5	

The real size operational log boom line used by Santo Antônio Energia was designed as a system with several modules that are installed across the river near to the facilities. The prototype modular set is composed of floaters encaged on a rigid frame structure that is connected to a longitudinal reinforced beam, which in turn is connected to a grid, as illustrated in Figure 3. The modules are then connected side by side forming a catenary-like shape line, seen in Figure 1. The average water line is located at mid height of the upper structure, leaving around 3.5 m of submerged height.

Figure 3. Installation of a real size log boom module

The 1:10 scale was adopted for the model to make it simple to build and handle. The log boom model was designed om CAD tools and manufactured from thin polycarbonate sheets due to its stiffness, availability of using waterproof bonding glue, and suitability of using laser cutting technique on this type of material. The float equipment was build up from PVC pipes and its convex extremity lids were 3D-printed. The final form of a module and its principal dimensions are shown on Figure 4. Each module of the log boom line is formed of three floaters, frame structure, stiffener beam, and grid. The model is composed of the connection of several modules passing a pivot axis through concentric holes of its endings.

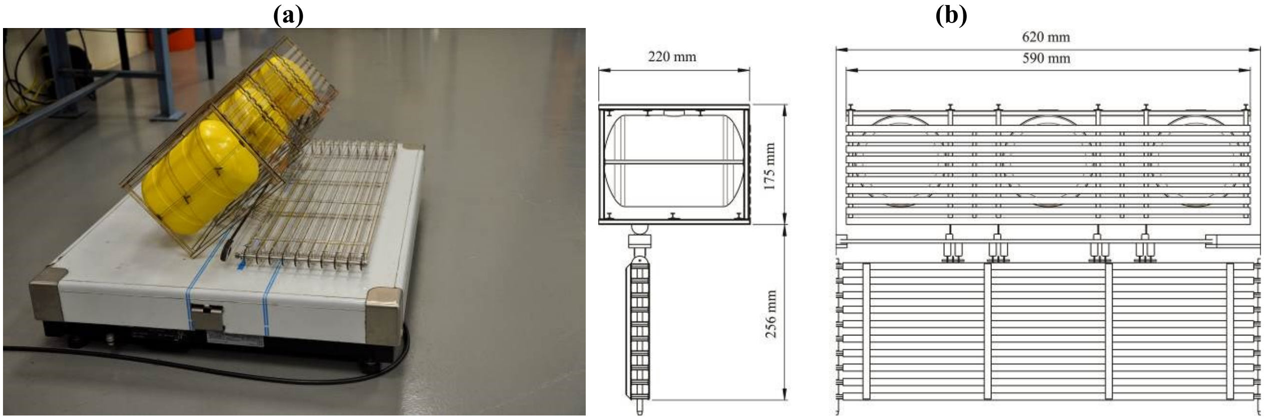


Figure 4. Final overview for a scale log boom module (a) and its dimensions (b)

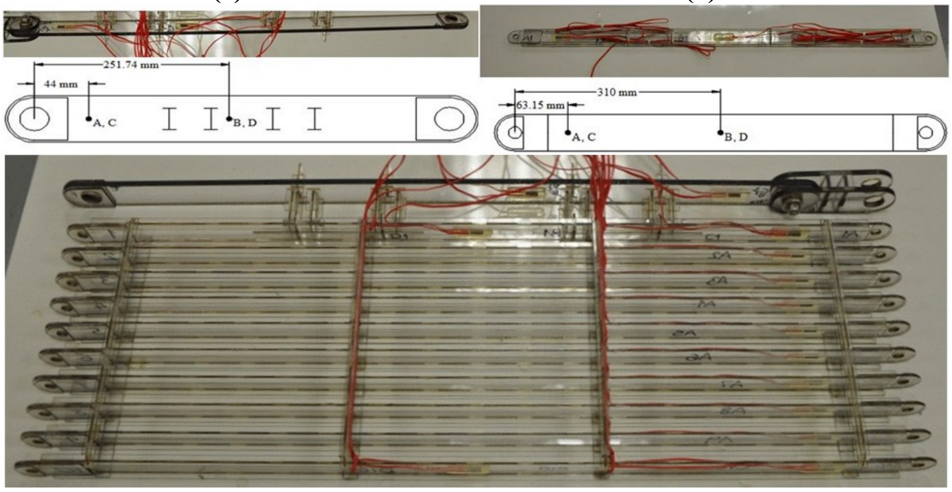
2.2 Instrumentation and Calibration

The instrumentation process was divided into two approaches: global and local instrumentation. The global instrumentation used to measure the external forces acting on extremities of the truncated model, representing the log boom anchorage system, was done with load cells. Eight S-Type S9M uniaxial load cells, produced by HBM, were used. Each one has a nominal measurement limit of 500 N and four of them were placed at each extremity of the line, distributing the total load among them. It is noticed by Figure 5 that only the intermedium beam and the lower grid that are connected to the load cells, leaving the floater with no attachment function.

Figure 5. Load cells placement on the model extremities

The local instrumentation scope was interested in measure the strain behavior on each beam of the grid and the stiffener beam during the tests, to understand how the stain is transferred throughout the structure, once for the full scale, they are submitted to high tension values for being the components that transmit the loads during its operation. To obtain some basic previous information about the strain field, these components were numerically tested using Finite Elements Method. The goal was to locate the stress concentration area to enhance the measurement sensitivity, and to avoid the high strain gradients, which can corroborate for unreliable measurements. Then, water strain gages, manufactured by Kyowa Electronic Instruments, are placed on some locations as shown on the schematics of Figure 6. Technical information about the strain gages are summarize in Table 2.

(a) **(b)**



(c)

Figure 6. Strain gages arrangement for the stiffener beam (a), girders that compose the grid (b), and their final assembly and connection (c)

The upper and lower girders of the grid and the stiffener beam have four strain gages each, indicated by points A, B, C and D, in Figure 6. Strain gages at the same region means they are attached on opposite sides. The intermediate girders have one strain gage each, at the A position, for simplification purposes. Otherwise the grid would present some cable fitting issues, meaning a massive channels amount over the model. A data acquisition system by Lynx (model A2161 and A2164), with a total of 29 channels, including the towing speed measurement, was used to condition the signal to convert them into digital format. The final overview of the instrumented elements assembled together is shown in Figure 7.

Table 2. Strain gages main characteristics

Model	KFWB-5-120-C1-11L1M2R
Gage Factor	2.10 ± 1.0%
Gage Length (mm)	5
Gage Resistance (Ω)	120.4 ± 0.4%

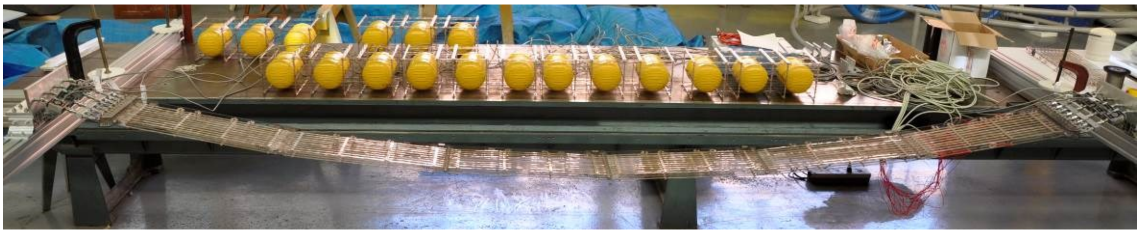


Figure 7. Assembly of the reinforced beam and grid with the load cells

Assuming the components are forced longitudinally, each instrumented part is individually calibrated by loading it in order to have a purely axial load provoking the strain gages. The apparatus consists of two simply pulleys, a string, and calibrated masses. In order to assure the strain gages behavior under water, the favorable thermal dissipation and its resin tightness, the instrumented elements were all submerged during calibration. Also, the water is a great heat sink fluid to dissipate the heat created by voltage excitation, which could deform the polycarbonate due its low heat dissipation.

2.3 Experiment setup

Once the idea is simulate an operating condition, the model was ballasted attaching lead stripes on the grid and over the top structure, without modification of the model frontal area, in order to minimize the drag interference.

The log boom line is designed to assume a catenary form, which can be either symmetric or asymmetric considering its extremities location or the flow incidence angle. Furthermore, the entire model has its width limited by the basin geometry, and in order to deal with this issue, the experimental assembly was adapted to allow both transversal (ΔT) and longitudinal (ΔL) variations between the extremity points. To allow a considerable longitudinal variation and with this, different incidence flow angles, the number of modules can be also increased. The tests are designed to maximize the amount of runs with as less variation as possible, considering the difficult of access on the fixation points. As the tests have interest in the hydrodynamic effect of the model, flat plates were attached at both extremities of the model line to reduce the interference of the structures and to better control the flow incidence, as seen in Figure 8.

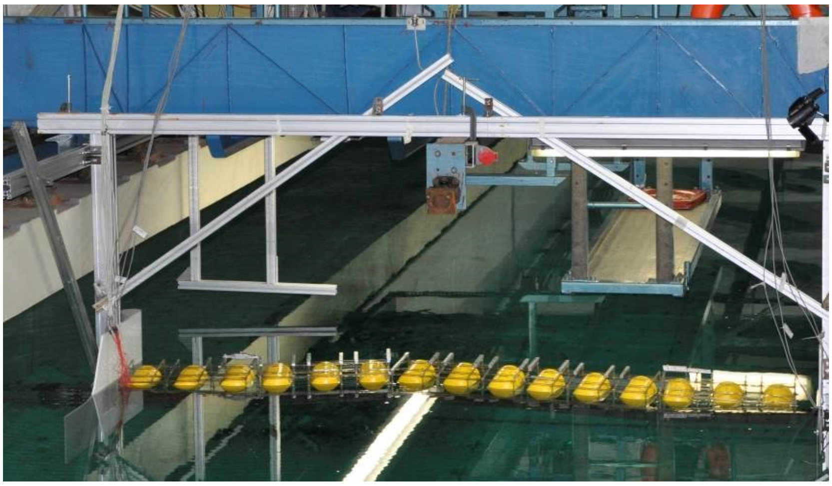


Figure 8. Log boom model and its fixation structure at the towing carriage

2.4 Experimental matrix

The variation parameters adopted for the testes were the carriage speed and incidence angle. Considering that the model will present a constant load distribution in the longitudinal direction, it was possible to predict the shape that the model would assume when being tested by a standard catenary formulation, and then define input parameters. From the model geometry and facility limitations, it is possible to define an experimental matrix for the tests, presented in Table 3. The value in the angle column represents the mean incidence angle, defined by the inclination angle of the line that connects both extremities of the model, as seen in Figures 9. Only the 5 modules configuration consists in a symmetric arrangement. The carriage speeds are defined from the Froude number relationship between the prototype and model dimension, considering water current values measured in the Madeira River.

The sketches for each one of the tested configurations are presented in Figure 9. Assuming the layout of Figure 9, the instrumented grid was set up at the left fixed extremity and the opposite extremity is translated longitudinally for each test configuration. The log boom articulations along the entire model are indicated by asterisks. The two vertical lines represent the side plates.

Table 3. Experimental Matrix

Number of Modules	ΔT and ΔL	Angle	Prototype Velocity	Carriage Speed
5	3.66 m and 0 m	0°	0.50 m/s 0.75 m/s 1.00 m/s 1.25 m/s 1.50 m/s 1.75 m/s 2.00 m/s 2.25 m/s 2.50 m/s	0.158 m/s 0.237 m/s 0.316 m/s 0.395 m/s 0.474 m/s 0.553 m/s 0.632 m/s 0.711 m/s 0.790 m/s
6	3.58 m and 2.3 m	32.7°		
7	3.58 m and 3.24 m	42.1°		
8	3.58 m and 3.9 m	47.5°		

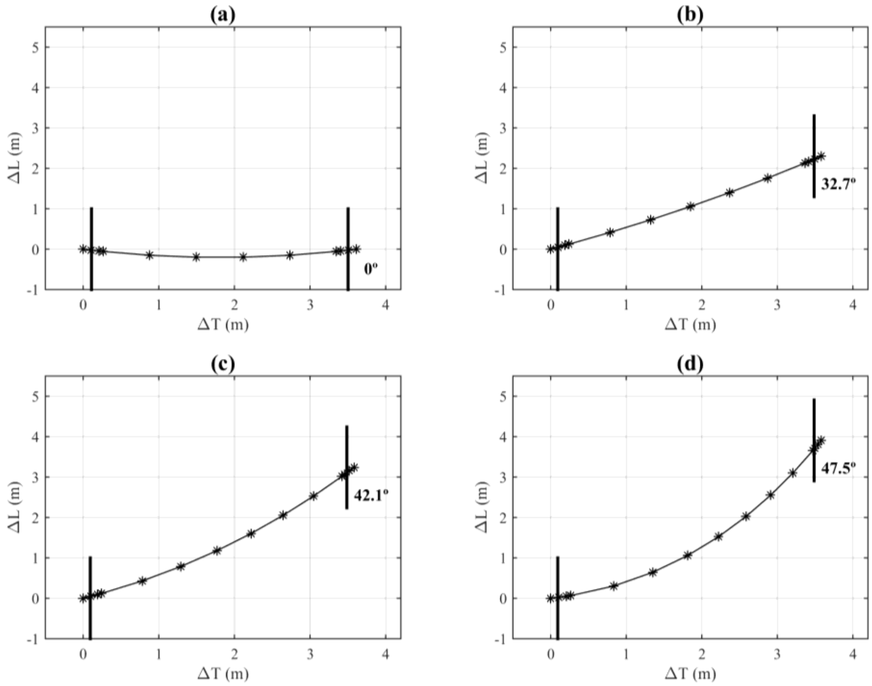


Figure 9. Catenary-like shape prediction for a) 5 modules, b) 6 modules, c) 7 modules, and d) 8 modules

3. RESULTS

The scale model has been tested, as shown in Figure 10. It is possible to note a sensible variation on the model sinkage and rotation of the floater frames as the towing velocity increases. Processed data from load cells are presented in Figure 11. It shows reasonably that the sum forces on both sides are very similar for the symmetric configuration, corroborating for the adopted methodology in the force distribution in the load cells. It is also possible to observe a reduction in the force with the increase of the incidence angle, even with the increase of the number of modules. This indicates, as expected, that each log boom module has a drag reduction due to inclination, being this effect more visible at higher velocities, as the global load presents a quadratic behavior in function of the velocity. Moreover, the total force of all non-symmetric on the right forward extremity presented a greater magnitude comparing to the left one, which is endorsed by the traditional catenary theory.

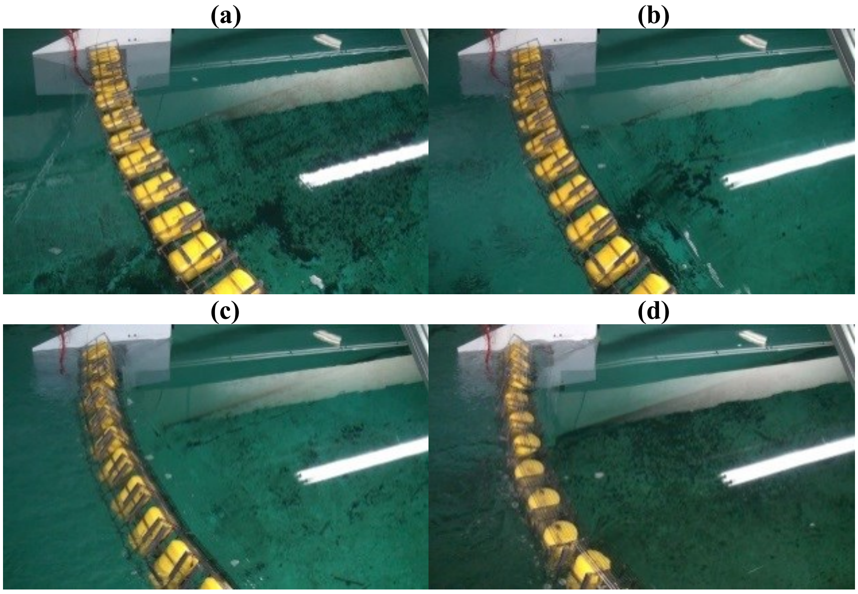


Figure 10. Log boom model tested in IPT's Towing Tank for a) 0.237 m/s, b) 0.395 m/s, c) 0.632 m/s, and d) 0.790 m/s, in 6 modules configuration

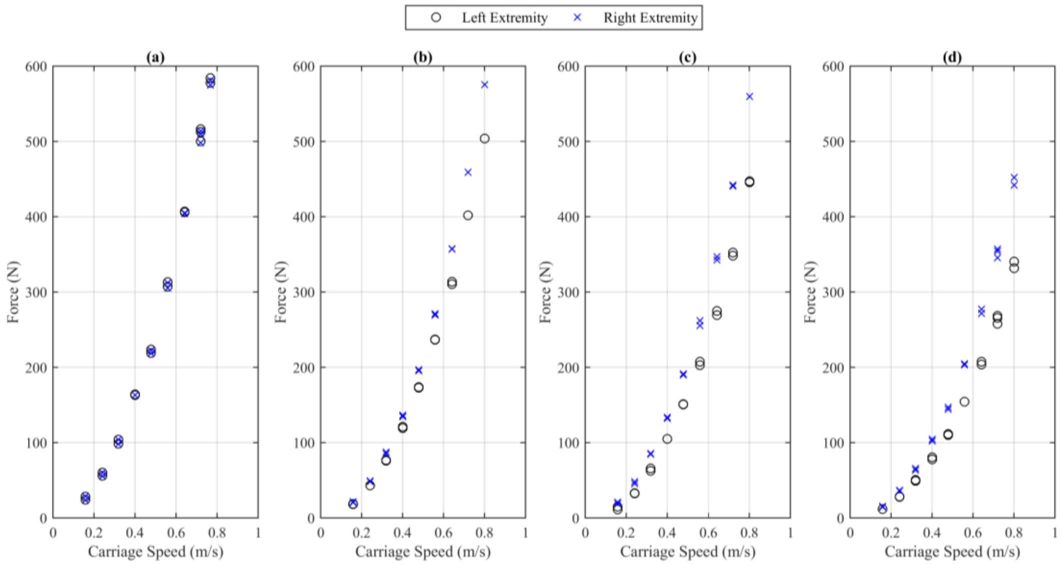


Figure 11. Sum of load cell forces measured on each side of the model with the increase of the carriage speed for a) 5 modules, b) 6 modules, c) 7 modules, and d) 8modules

In Figure 12 is presented the comparison between the loads measured by all load cells at the left end and the strains gages, and it is verified that they are quite similar at low and medium velocities, indicating that the strain gage measurements can be used to estimate the total strain transmission along the model as it presents a major axial behavior, as seen in Figure 12. On other hand, there is a divergence of values at higher velocities, which is believed to represent the torsion of the model, from the interaction with the adjacent module, and some bending moment provoked by the forces generated by the floaters structural frame rotation, showed in Figure 10. The data presented a reasonable quadratic tendency in respect to the velocity, except for the last configuration that present a more linear behavior. It is important to note that the configuration with 6 modules does not have repetition data, as a result of a repair operation done during the tests.

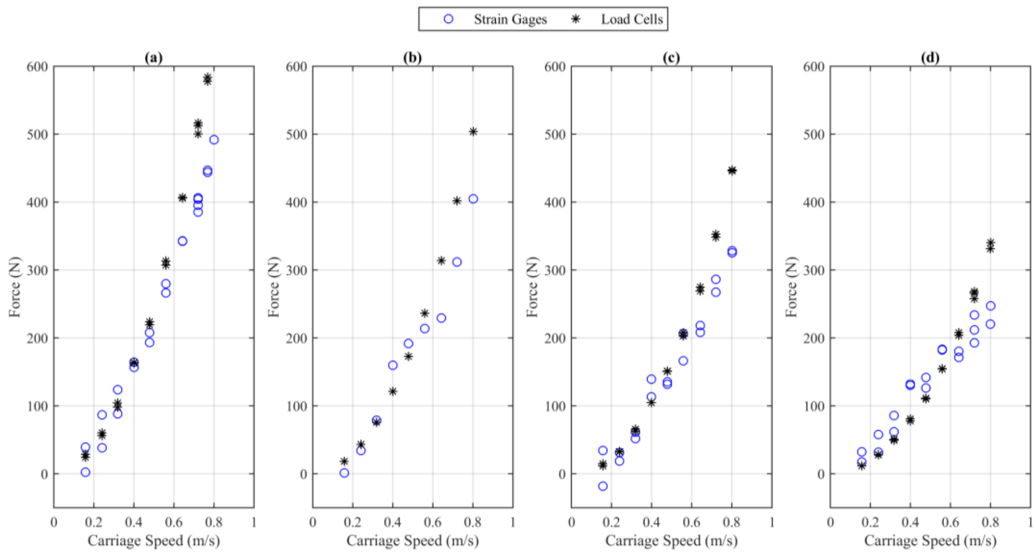


Figure 12. Comparison between sum of forces in load cells and strain gages with the increase of carriage speed for a) 5 modules, b) 6 modules, c) 7 modules, and d) 8modules

Figure 13 shows quantitatively the portion of load that is attributed to the reinforced beam and grid, treating each one of them as a single component, i.e., summing the respective and individual forces measured for each strain gage. Negatives values are assumed to be compression, while positives values are assumed as traction. For three of the four cases, the reinforced beam represents around 80% of the total load. All the cases present a compression behavior due to asymmetry of the load acting on the grid, being more characteristic in the case with 8 modules, which leads to similarity between the total and reinforced beam values for that configuration.

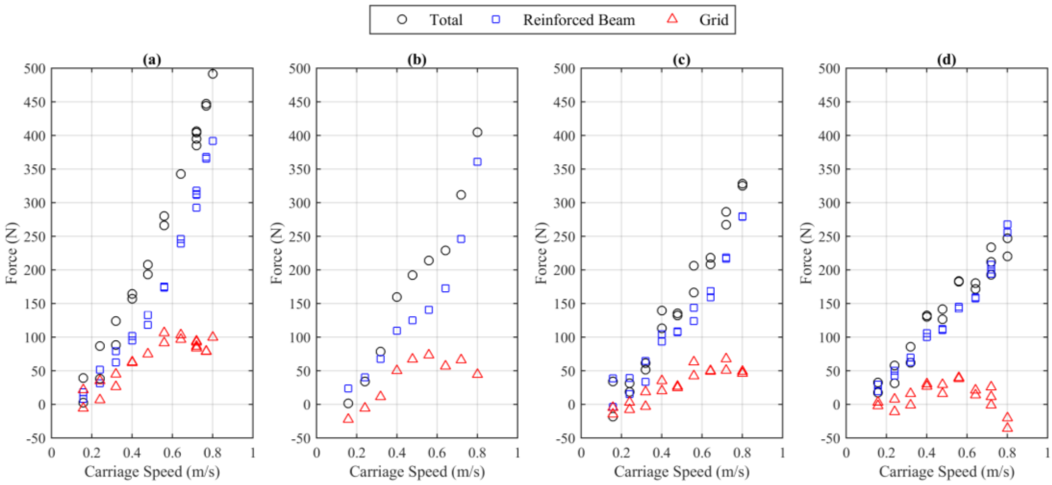


Figure 13. Measurement data from reinforced beam and grid for a) 5 modules, b) 6 modules, c) 7 modules, and d) 8 modules

As the reinforced beam being responsible to the major part of the line structural resistance, Figure 14 shows the individual gages behavior for this component. Knowing that gages A and C are placed at upper and lower part of the beam tip, it is believed that this element has a bending stress on its extremities, which explains the compression on C and traction on A for the initial velocities. On other hand, B and D, located at the medium region, do not present an asymmetric aspect, appearing to be purely axial loaded most of the time due to their symmetric localization.

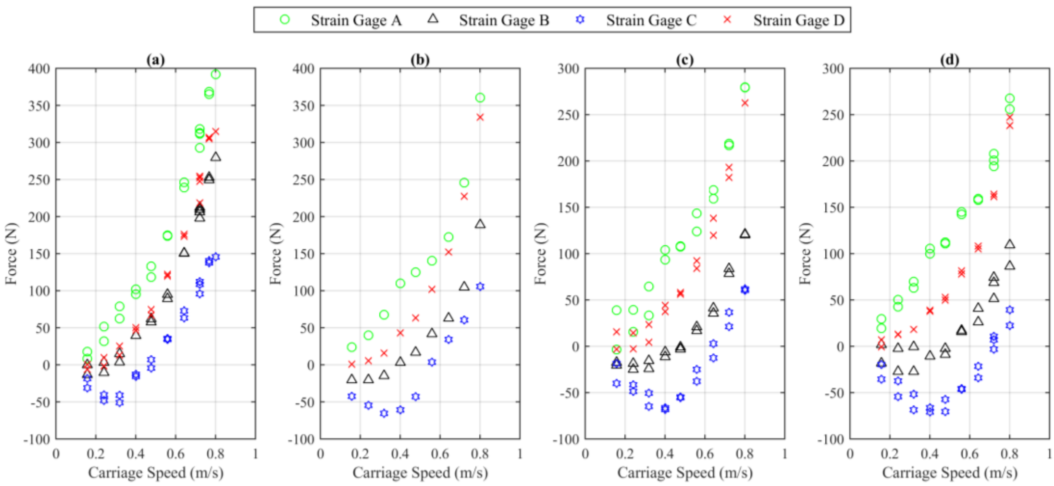


Figure 14. Reinforced beam strain gages measurements with the velocity for a) 5 modules, b) 6 modules, c) 7 modules, and d) 8modules

4. CONCLUSIONS

This paper presented a structural analysis for a reduced scale model of a hydropower plant debris containment grid. The truncated model was designed, built, instrumented, and tested in the IPT's Towing Tank. The experiment was developed to understand how the structural strain behaves in the presence of symmetric and asymmetric hydrodynamic loads in a controlled stream flow.

The results demonstrated a qualitative acceptable accuracy, given to the repeatability of the tests and the instrumentation process. It was possible to assure that the load cells were set properly, once they allowed a reasonable analysis of the force acting on the model for each module configuration, with the increasing on towing speed and incidence angle. Beyond that, it was observed that the instrumented module follows a complex structural tendency, mainly at higher velocities. When analyzed separated, the reinforced beam showed itself as the essential element, resisting to the majority of the load generated by the model interaction with the fluid stream.

In order to improve the measurements reliability, a calibration procedure involving all the components assembled together will be performed, as well as the installation of strain gages in other areas.

In the future, analogous analysis will be executed to the experiments with several conditions of log accumulation, showed in Figure 15.

(a) **(b)**

Figure 15. Top (a) and submerged view (b) for test with scale logs accumulation in the IPT's Towing Tank

5. ACKNOWLEDGEMENTS

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