FINITE ELEMENT MODEL OF CLOSED COMPOSITE CYLINDER AND ITS EXPERIMENTAL VERIFICATION

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Abstract. The paper presents the experimental verification of the numerical model developed for a closed composite cylinder structure. The operational modal analysis (OMA) techniques are used for modal parameter estimation of the cylinder tested. The impact hammer was used for excitation and the network of piezo films measured the vibration response providing experimental estimation of the cylinder modal parameters. The modal assurance criterion was applied to initially identified modes that allows validating the most stable modes of the closed composite cylinder. Then, the modal parameters of stable modes were used for finite element (FE) model verification. Good agreement between measured and modelled frequencies and mode shapes up to 400 Hz was achieved.

Keywords: composite, cylinder, experiment, frequency, numerical.

Introduction

The modern laminated composite cylindrical shells are widely used as structural elements in civil, aeronautical, marine and mechanical engineering due to their high specific strength and design performance. However, these advantages are balanced by a lower damage resistance of composites. External mechanical and cyclic loads as well as environmental influences can damage the laminated composites due to their low resistance to delamination. Structural damage can cause the failure leading to undesirable consequences and losses. Thus, structural health monitoring (SHM) and damage detection is one of the most important tools for maintaining the integrity and safety of the composite structures [1-3].

SHM techniques, like ultrasonic and radiographic inspections, acoustic emission, infrared and thermal testing, eddy-current methods [4-6] are applied widely. These techniques ensure a high resolution, which is effective in fault identification. However, the above mentioned techniques are applicable to non-operating structures only and sometimes require a dismantling of a monitored object. When applying these techniques most of operating facilities have to be stopped for maintenance that is ineffective due to operational losses. For other facilities operation halt is highly problematic if not impossible. For instance, transport vehicles, civil infrastructure facilities (bridges, dams), remote pipelines and wind turbines require operate non-stop. Mostly preventive techniques are used to perform monitoring of such structures, which require stopping the operations for testing procedures.

More efficient way to perform SHM is to check a structural condition without stopping the facility. Especially, such approach is effective for condition-based maintenance [7]. Thus, the facility is only stopped, when a fault is detected and has to be repaired. Technical condition of the critical structures has to be monitored in real time, to detect the fault well before it becomes a liability. This gives operators and engineers valuable time to plan maintenance. To ensure this way, each structure should be equipped with individual monitoring system. Such systems should be produced and used on a massive scale, and therefore conform to the requirements for serial production.

To increase economic effectiveness and safety of operating facilities, the vibration-based methods are used, which give way to a new generation of structural health monitoring. Traditional Experimental Modal Analysis (EMA) is widely used for structural testing, for example, to ensure that the self-resonances of structures do not coincide with the pronounced frequencies of acting forces [8]. EMA requires a controlled excitation of the structure, which is unfeasible for large structures like bridges, wind turbines and so on. There are particular vibration-based techniques Operational Modal Analysis (OMA) [9] that are the most promising for operating facilities. OMA, on the other hand, assumes certain excitation conditions and does not require excitation to be manually controlled – usually natural forces excitation is used, and this is sufficient to excite structural modes. Acquired vibrational data is then analysed using OMA signal processing techniques, like stochastic subspace identification [10] and frequency domain decomposition [11]. As the result, modal parameters are obtained, which directly correlate to the structural features – mass, stiffness, and damping [12-13]. If any of the three features change (e.g. due to a damage), the modal parameters also change. By monitoring modal parameters of a structure, it is possible to monitor the structural condition. These processes enable SHM without compromising operations of a facility. There are commercial software packages, like Artemis, which allow OMA methods application. There are samples of trial SHM for civil structures [14-15], where changes of modal shapes or curvatures are claimed as most sensitive to local damage. In application to a helicopter, the authors in [16] studied the change of modal shapes of the rotating blade as the tool for diagnosis of structural modifications. There are trial OMA based SHM systems developed, including systems developed by the authors [17-18], that are being used in aviation, for ships, pipelines, sea structures, wind energy structures. Aiming at condition-based maintenance, the task of OMA based SHM system is modal state monitoring of an operating object, fault identification and localization, after exceedance of modal state boundaries.

The aim of this study is experimental verification of the finite element (FE) model developed for the closed composite cylinder with rigid ends. Verification is performed using modal analysis in real construction. Natural frequencies and modal shapes are the effective parameters to verify and calibrate numerical models. The verified FE model is supposed to become a baseline for further studies of similar typical cylinders for damage identification. The experimental part of the study has to verify also the production technology of the specimen, its static strength and modal testing methodology.

Materials and methods

The discussed study is the initial stage of the project to develop an operational prototype of structural health monitoring (SHM) system for typical structures operating under different conditions. The modal passport approach used as methodical basis includes dependence functions that consider influence of different factors on modal parameters. To research these factors, the series of typical structures have to be produced as specimens for testing. The closed composite cylinder with rigid ends was accepted as the typical composite structure. The prototype of specimen (Fig.1) was fabricated to refine the production technology of typical structure (test specimen) and test methodology.

The circular cylindrical shell (tube 300 mm diameter) is formed by four layers having fibers orientation ± 45° to alongside axis and made from glass fiber reinforced polymer (GFRP) composite. To ensure the mechanical strength of the sample, the cylindrical part is glued into the recesses of the plywood flange to a depth of 15 mm. The network of piezo-electric sensors measuring shell strains are allocated around the cylindrical part specimen. After gluing the sensors and wires, the cylindrical part is laminated with a protective layer of 50 g/m^2 satin woven glass fiber. The prototype dimensions are 788x360x360 mm, 1.45 mm wall thickness, and 4.43 kg mass.

Fig. 1. **The prototype of specimen**

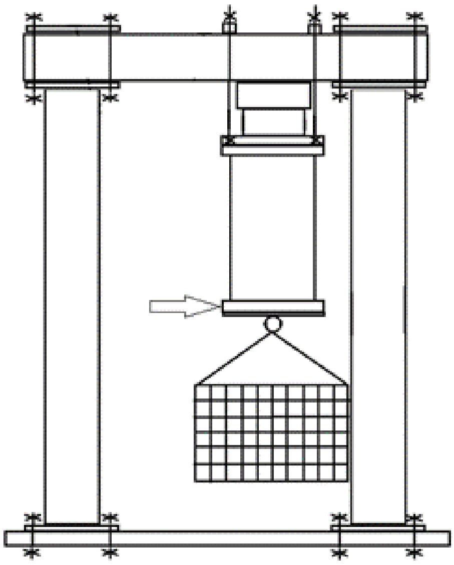

Fig. 2. **Test bench for modal testing**

For tuning the modal model, the pre-production sample (prototype) was fabricated with a limited number of sensors distributed over the cylindrical surface. The typical specimen has an integrated network of film-type piezoelectric sensors with connecting wires and connectors. The prototype has a limited number of sensors that formed two clusters of circularly and lengthwise oriented sensors (25 and 20 pieces accordingly). The sensor connectors on the top end are wired to the measurement unit Type 3053-B12/0 (Brüel & Kjaer). For modal testing of the specimen, the special test bench is used that includes the square tube frame fixed to a vibration-insulated foundation (Fig. 2). The specimen is vertically oriented in the test bench and is fixed at the top end. The static load test is scheduled for check of a structural integrity of the prototype specimen as well as operability of the sensors and connections.

For modal testing of the prototype, the impact hummer was used for excitation that affected the bottom of the specimen. The network of piezo films provided the response to excitation as strains in the distributed measurement points. The *Artemis* software applying OMA techniques computes modal parameters of the specimen from the measured strains. To highlight most stable modes for further identification, the modal assurance criteria were applied to plenty of computed modes.

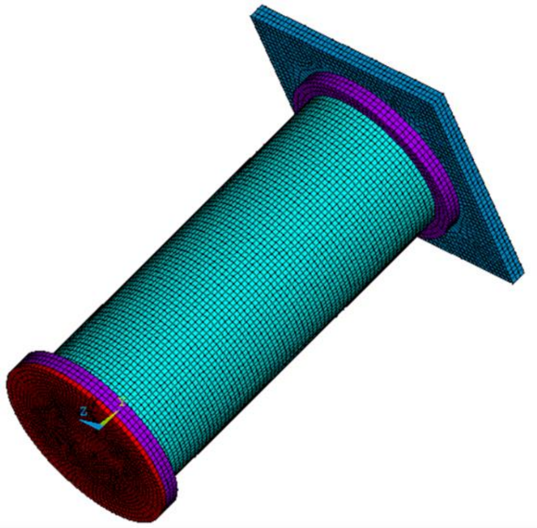

Fig. 3. **Structural specimen: FE model**

3D Finite element model (FEM) of a closed composite cylinder was built using ANSYS16.0 software to replicate the experimental response. 8-node structural solid element SOLID185 and 4-node structural shell element SHELL181 were selected for modelling of rigid plywood discs and layered composite cylindrical shell, respectively (Fig. 3). The gravity and bolted connection in the plywood plate were not included in the FE model and were ignored during calculation. The clamped boundary conditions were applied on the top of the wood square plate according to the experimental set-up and realized by putting the constraints on nodes, when all degrees of freedom are fixed. Block Lanczos method was used for natural frequencies extraction of the closed composite cylinder. Before numerical analysis, the mesh convergence studies were performed to obtain the results with an acceptable accuracy.

Table 1

Modelled material properties

Property	GFRP	Plywood
Elastic modulus, E_1, GPa	30.9	8.0
Elastic moduli, $E_2 = E_3$, GPa	8.3	-
Shear modulus, $G_{12} = G_{13}$, GPa	2.8	-
Shear moduli, G_{23}, GPa	3.0	-
Poisson's ratios, $\upsilon_{12} = \upsilon_{13}$	0.32	0.3
Poisson's ratio, υ_{23}	0.23	-
Density, ρ, kg·m^{-3}	1700	800

The material properties of glass fibre composite polymer used in modelling of composite cylinders were obtained using a non-destructive numerical-experimental method for the identification of the elastic properties [19-22]. This method consists of several stages: (a) the selection of the supposed values of elastic constants and creation of the plan of the experiment; (b) numerical modelling of the laminated composite plate for the elastic constants selected; (c) approximation of the obtained data; (d) experimental testing of the laminated composite plate; (e) minimizing the error functional between the numerical and experimental data of structural responses for identification of the material properties. The material properties used in numerical modelling are presented in Table 1.

The data obtained from modal tests of the prototype allows computation of experimental modal parameters. The shapes and frequencies of experimentally obtained modes are compared to the data of FE models for identification.

Results and discussion

The first eight natural frequencies obtained from FEM are presented in Fig. 4. The modes and the corresponding modal frequencies of the circular cylindrical shell are defined by any combination of axial and circumferential modes. It can be seen that with increases of frequency more than one half waves are observed (7 and 8 frequencies).

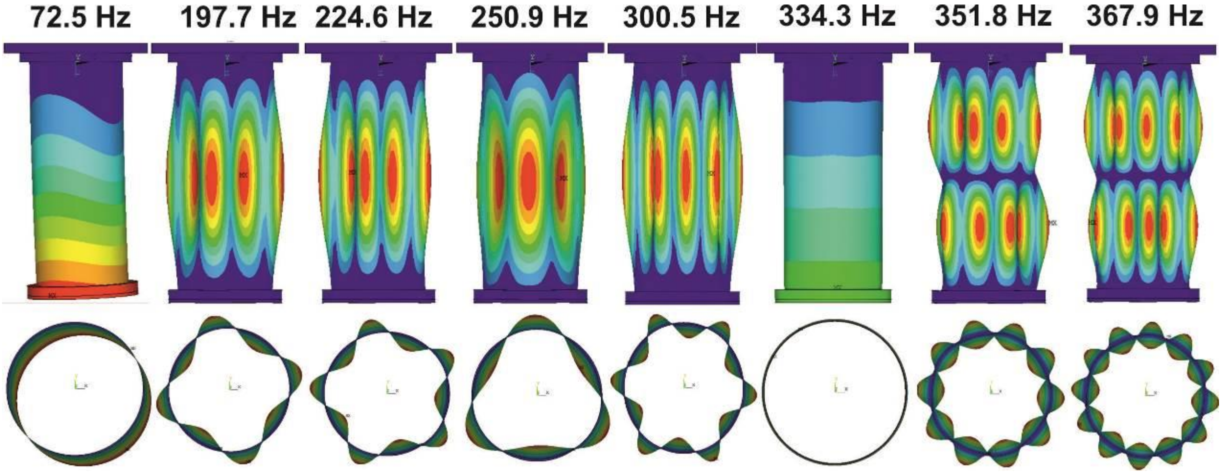

Fig. 4. **Numerically modelled axial (top row) and circumferential (bottom row) mode shapes of the closed composite cylinder structure**

The static load test did not affect the structural integrity of the sample and the operation of the sensors and sensor connections, which confirmed the effectiveness of the prototype design and materials/technologies. The *Artemis* software applying OMA techniques computes modal parameters of the specimen from the measured strains. Fig. 5 illustrates the most pronounced modal shape by Artemis software. The three frequencies (4th, 7th, and 8th) were obtained from the experiment but the mode shapes not clearly identified.

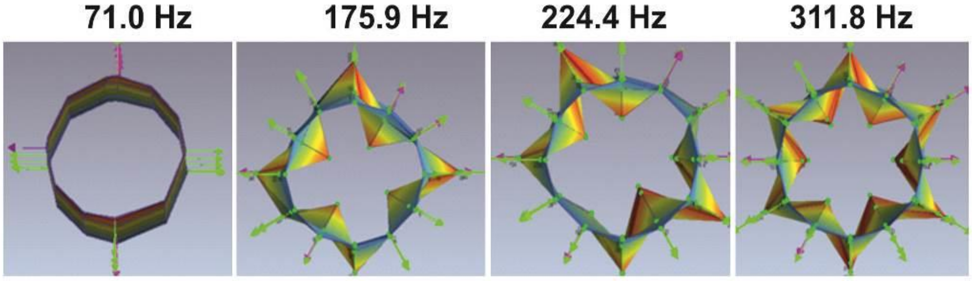

Fig. 5. **Sample of experimentally measured mode shape**

Data in Table 2 demonstrate the comparison between the natural frequencies determined by FEM and from the experiment, where *m* and *n* are the axial and circumferential wavenumbers. It can be seen that stable mode and corresponding natural frequencies are present in this table. The largest percentage difference between experimental and numerical frequencies is observed for the second mode shape

(11%) and seventh mode shape (8.2%). For all other modes percentage change does not exceed 3.8%. Average error of the identified modal frequencies between two cylinders is 4.6%. Two of eight predicted modes (250.9 Hz and 334.3 Hz) have not been identified using experimentally measured and computed modal parameters. The reason of missing modes is the limited number of piezoelectric sensors that were used in the prototype specimen. The small percentage difference confirms accuracy of the FEM developed and reliability for further studies of similar typical cylinders for damage identification.

Table 2

Comparison of natural frequencies between FEM and experiment

No	Mode (m, n)	ANSYS frequencies f_{FEM}, Hz	Experimental frequencies f_{exp}, Hz	Modal frequency percentage change Δ, %
1	(0,1)	72.5	71.0	2.1
2	(1,4)	197.7	175.9	11.0
3	(1,5)	224.6	224.4	0.1
4	(1,3)	250.9	-	-
5	(1,6)	300.5	314	3.8
6	(1,0)	334.3	-	-
7	(2,5)	351.8	323.1	8.2
8	(2,6)	367.9	359.6	2.3

Conclusions

1. The finite element model of the specimen (composite cylinder with rigid ends) was developed and the modal parameters (frequencies and shapes) of the specimen were computed. The production technology of the composite specimen with an integrated vibration measurement system is developed and validated. The special test bench for modal testing is created and the modal testing technique is refined.
2. Comparative analysis between experimental and numerical results of composite cylinder made from glass fiber reinforced polymer composite with rigid ends was considered in frequencies range up to 400 Hz. The largest percentage change in the modal frequencies between experimental and numerical cylinders was 11% for the second mode shape and 8.2% for the seventh mode shape, respectively. Average error of the identified modal frequencies between two cylinders is 4.6%.
3. The experimental verification of the numerical model of the specimen demonstrates good agreement with the experimental data of modal analysis. The tuned model of the specimen will be used to research the influence of the technical condition and ambient factors on the modal properties.

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Author contributions

Conceptualization, A.M. and A.C.; methodology, A.M.; software, A.K.; validation A.M.; formal analysis, A.S. and A.K.; investigation, A.M.; data curation, writing – original draft preparation, A.S. and A.K..; writing – review and editing, A.M.; visualization, A.S. and A.K.; project administration, A.C.; funding acquisition, A.C.; All authors have read and agreed to the published version of the manuscript.

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