論文の内容の要旨

Dissertation Abstract

論文題目

Indentation Response and Damage Monitoring of Foam-Core Sandwich Structures
（フォームコアサンドイッチ構造の押し込み挙動と損傷モニタリング）

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Introduction

Composite foam core sandwich structures offer many benefits over normal composite laminates. The relatively weak core and thin faces make them however rather vulnerable against transverse indentation or impact loadings. Especially indentation loading or low velocity impact can leave only barely visible damage in the face sheet while the core and adhesive layer can be significantly damaged thus having notable effect on the strength and stiffness properties of the structure. Environmental conditions can also affect the indentation response of the sandwich structures by degrading the properties of the core material leading to even more severe damage inside the structure. Due to the barely visible residual dent remaining after indentation or impact, visual inspection becomes difficult and therefore a way to accurately detect these kinds of damages and to assess their severity is also needed.

This study focused on the indentation response and damage monitoring of foam core sandwich structures. Especially the effect of environmental conditions was considered. Indentation response of sandwich structures at various temperature and humidity conditions was studied experimentally and by finite element analysis. Also the compressive and tensile behavior of the foam core material was studied, as the indentation response depends on the loading response of the core material. A high resolution fiber optic distributed strain monitoring system was applied to monitor the sandwich structures and to detect the barely visible damages induced by indentation loading and low velocity impact.

1. Indentation response of foam-core sandwich structures

First, the loading response of the polymethacrylimide (PMI) foam core material was studied

experimentally by conducting compression-tension loading cycle tests at various temperature and humidity conditions. Effect of the environmental conditions on the foams properties was then observed. The high temperature and humidity conditions degraded the properties of the foam as its polymer material was softened and plasticized by the temperature and diffused moisture. Conditioning at humid environment for even a short period caused notable reduction in the foams compressive properties. The combined effect of temperature and humidity was notably larger than the effect of only temperature or humidity. The response of the foam also changed from brittle to ductile as the moisture content of the foam increased.

Indentation response of sandwich structures was then observed experimentally. Indentation loading tests were conducted with beam specimens at various temperature and humidity conditions. The indentation strength and stiffness of the sandwich specimens was notably degraded by high temperature and humidity conditions and was closely related to the foams loading behavior at the same conditions. Also the size of the residual dent increased with increasing temperature and especially with increasing humidity.

2. Finite element analysis of indentation response and residual state

Finite element analysis of the indentation loaded sandwich beams was then conducted. The crushable foam material model in the ABAQUS software was used for the core of the sandwich beams. Material properties and loading behavior of the core were adjusted based on the results of the foam loading experiments. The indentation loading behavior was predicted well with the used material data. Response at high humidity and temperature conditions however differed from the experiments due to different moisture content of foam core in the sandwich beams and the foam specimens used to define the foams properties. The size of damage in the core was also related with the residual strains for damage detection purposes. However, prediction of the unloading behavior and residual state was less accurate due to the simplified tensile behavior of the crushable foam model.

To overcome limitations of the crushable foam model, an improved material model for the core material to be used in the finite element analysis was suggested. The new model was based on the crushable foam in ABAQUS. Degradation of elastic modulus during compression and tensile response of the foam were implemented based on experimental data. The predicted unloading behavior of indentation loaded sandwich beams was notably improved by the new model compared to the crushable foam model. The new model was also able to provide more accurate prediction of the residual state as was later shown in the damage monitoring experiments.

3. Damage monitoring in foam-core sandwich structures

Finally, a fiber optic distributed strain monitoring system for damage monitoring in foam core sandwich structures was presented. A Rayleigh scattering based system was used to monitor strain distribution along optical fibers embedded in the adhesive layer of sandwich structures. The system provided high resolution strain data during indentation loading. Damage detection ability of the system was studied by conducting experiments using sandwich beam and panel specimens. Sandwich beam specimens were indentation loaded at various temperature and humidity conditions and the strain distribution in the adhesive layer was monitored. The effect of environmental conditions on the indentation response was also seen in the measured strains. Comparison with analysis results showed good correlation, especially with the improved model. Detection ability was also verified on sandwich panel specimen. Finally, real life sandwich panel demonstrator was used to show the system's ability to detect low velocity impact damage. The location and size of the damages could be accurately detected even when no damage was visible in the face sheets.

Conclusion

This thesis has shown how the environmental conditions, the temperature and humidity, affect the response of the foam material in foam core sandwich structures and thus the indentation response of the sandwich structures. The indentation response was seen to be closely related to the foam materials behavior under loading. The indentation response could therefore be predicted well with finite element analysis by using the experimentally obtained material properties for the foam core. By implementing the experimentally observed unloading and tensile behavior of the foam material into the material model, improved predictions could be made about the residual state of indentation loaded structures. Finally, damage monitoring of sandwich structures was conducted using distributed optical fiber sensors embedded into the structure. The monitoring system could accurately detect the location and size of the damage by observing the strain distribution in the structure during and after loading. Damage detection ability and applicability of the system into real-life structures was verified by low-velocity impact tests on large scale sandwich panel.