



HAL
open science

Validation of Structural Parameters As Damage Indicators for Monitoring Plates in the Post Buckling Regime

Christoph Viechtbauer, Martin Schagerl, Kai-Uwe Schröder

► **To cite this version:**

Christoph Viechtbauer, Martin Schagerl, Kai-Uwe Schröder. Validation of Structural Parameters As Damage Indicators for Monitoring Plates in the Post Buckling Regime. EWSHM - 7th European Workshop on Structural Health Monitoring, IFFSTTAR, Inria, Université de Nantes, Jul 2014, Nantes, France. hal-01022083

HAL Id: hal-01022083

<https://inria.hal.science/hal-01022083>

Submitted on 10 Jul 2014

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

VALIDATION OF STRUCTURAL PARAMETERS AS DAMAGE INDICATORS FOR MONITORING PLATES IN THE POST BUCKLING REGIME

Christoph Viechtbauer^{1,2}, Martin Schagerl^{1,2}, Kai-Uwe Schröder³

¹ Institute of Constructional Lightweight Design, Johannes Kepler University Linz, Altenberger
Straße 69, 4040 Linz, Austria

² Christian Doppler Laboratory for Structural Strength Control of Lightweight Constructions,
Johannes Kepler University Linz, Altenberger Straße 69, 4040 Linz, Austria

³ Chair of Engineering Mechanics, RWTH Aachen, Kackertstraße 15, 52072 Aachen, Germany

christoph.viechtbauer@jku.at

ABSTRACT

The Structural Health Control (SHC) concept is a novel and overarching approach to monitor the strength of a structure online and in realtime over its lifecycle. In the center of the SHC approach is the structural analysis of the monitored part. It provides the information to identify structural parameters as damage indicators. With this information an optimized sensor layout can be defined to monitor the damage indicators in a smart way. The monitoring system is therefore referred as SmartSHM system.

This article is about the experimental validation of the SmartSHM concept within the SHC approach. The SmartSHM system is tested at a simply supported thin plate under compressive loading close to ultimate load. In the post-buckling regime bending occurs which causes high tension stresses at the plate's surface despite of the compressive loading. These stresses can initiate a crack due to fatigue. Therefore these regions are monitored with a SmartSHM system. Cracks were initiated to prove the functionality of the proposed SHM concept.

KEYWORDS : *Structural Health Monitoring, compression test, post-buckling regime, damage indicators, cracked structure*

INTRODUCTION

There is still a large interest on researching on SHM-Systems. In general, most of these SHM-Systems are concentrating on damage detection, damage localization, sensor development and signal processing, see [1]. The so called *Structural Health Control* (SHC) approach introduced by [2] focuses more on the structure and its behavior when damaged. It conjuncts modules such as structural analysis, flaw assessment, flaw prognosis as well as regulation and safety aspects and condition based maintenance (flaw refers to both damage and defect). Firstly, to observe and secondly to predict the safety of the structure. All these mentioned modules are embedded in a feedback control loop to ensure the integrity of the observed structure.

The structural analysis module plays an important role within the SHC approach. It provides all the information of the structure which is generated in the sizing process of the structural part. By means of this information an optimized sensor layout is defined to monitor the damage indicators. As the monitoring system uses given data in a smart way it is referred as *SmartSHM* system. In addition to that the information within the structural analysis module is updated with the measured data from the SmartSHM system. Flaw assessment and flaw prognosis therefore use the structural analysis module also as data base.

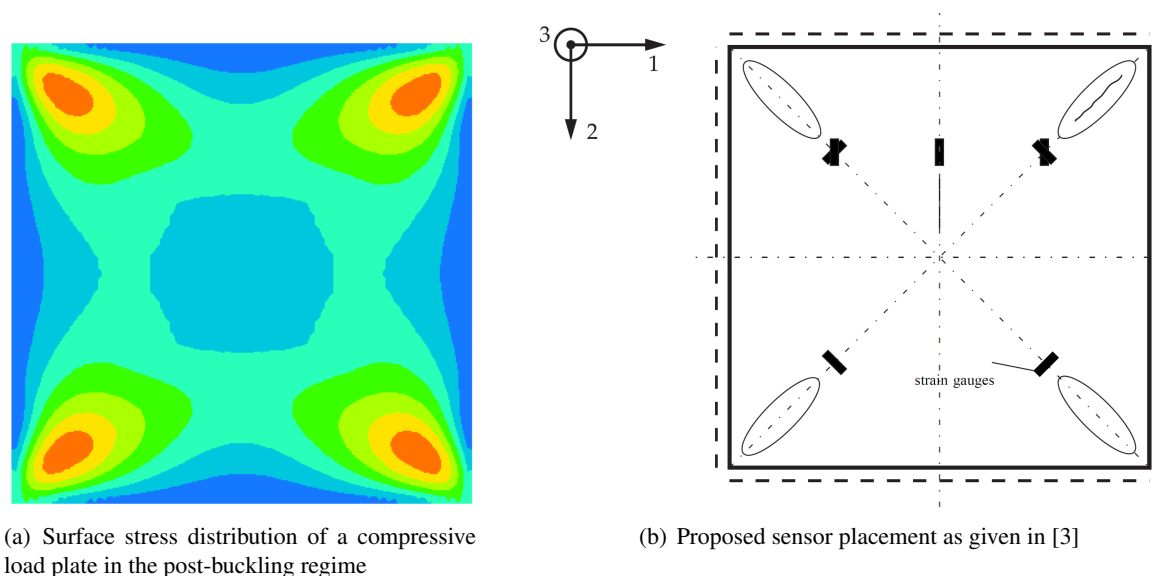


Figure 1 : Structural analysis results and the proposed optimal sensor placement

APPLICATION OF THE SMART SHM APPROACH ON A PLATE UNDER COMPRESSIVE LOADING

Using the information which is provided by the structural analysis to identify changes in the structural behavior due to damage is the driving idea of the SmartSHM approach. During the sizing process the structural analysis provides the expected structural condition (e. g. a particular strain distribution). Damage causes deviations in the structural condition. Some SHM systems are focusing more on measuring the damage itself, e. g. a crack length. The Smart SHM approach is to measure the effects on the structural behavior caused by the damage, e. g. the redistribution of strains. This provides the advantage to use robust and reliable sensors which also can be used in a combination to monitor a simple damage indicator.

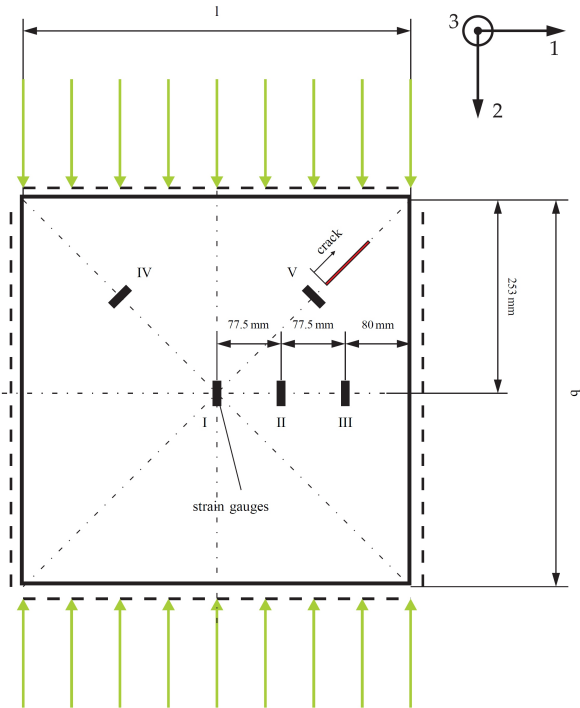
However, in this article the major focus is on the experimental validation of structural parameters identified as damage indicators by a structural analysis of a compressive loaded plate in the post buckling regime in [3]. Therefore, structural parameters (in our case specific strain distributions) have been identified by a FEM-model as depicted in Fig. 1 (a). The plate is a square plate of aluminium alloy 5005 with a yield stress of $R_{p0.2} = 158 \text{ MPa}$ and an E-Modulus of $E = 74700 \text{ MPa}$. The length of the plate is $b = 470 \text{ mm}$ and its thickness $t = 2 \text{ mm}$. It is simply supported on each side. The stress distribution in Fig. 1 (a) indicates clearly that the maximum tensile stresses occur in the corner regions after onset of buckling which is a remarkable fact as the component is compressive loaded. With this result the failure mode can be clearly defined: a possible crack initiation in the corner regions due to fatigue loading in the post-buckling regime. Furthermore, the structural analysis result proposes the measurable value (which is strain) and the optimal sensor placement as depicted in Fig. 1 (b). The SmartSHM set-up for a compressive loaded plate follows the recommendations given in [3]. The difference of the corner strains serves as damage indicator: in an undamaged plate the strains are of the same amount and the difference is zero while damage will cause an unsymmetric distribution. The corner strain difference becomes not equal to zero and, therefore, indicates a crack in the corner regions. Additionally the evaluation of the strains serves for a loads monitoring.

VALIDATION OF STRUCTURAL PARAMETERS AS DAMAGE INDICATORS

The proposed structural damage indicators should be validated in an experiment. However, the experiment is based on a test bench, as depicted in Fig. 2 (a) and on a specimen itself which is equipped



(a) Test bench for the post buckling experiment in our structural laboratory



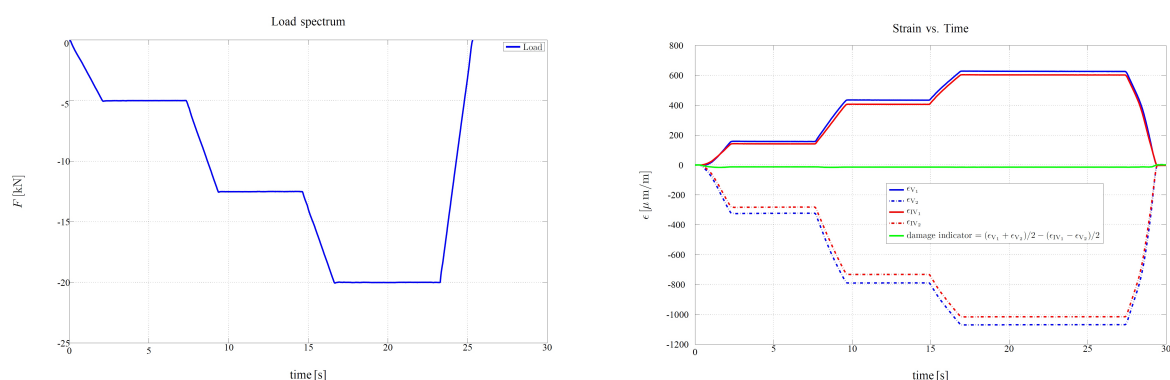
(b) Adapted optimal sensor placement for the validation of the structural parameters as damage indicators [3]

Figure 2 : Experimental set up for the validation of the damage indicators

with the proposed sensors, see Fig. 2(b). Firstly, the test bench was designed in our laboratory to simulate the buckling behavior of thin-walled structures in the buckling and post buckling regime. In the considered case a plate based on simple supported boundary conditions was used for the investigation. Secondly, the specimen is equipped by strain gauges as depicted in Fig. 2(b). However, the placement of the strain gauges is slightly different in comparison to the proposed placements as depicted in Fig. 1(b): Due to the homogeneous strain distribution up to buckling onset the strain gauges for the loads monitoring do not care at which longitudinal position they are applied. For reason of simplification regarding sensor application strain gauges I,II and III were applied in the middle of the plate. Furthermore, to possibly measure the load and the expected stress redistribution in the post buckling regime an additional strain gauge II was applied. Due to symmetric reasons just the right hand side was applied by strain gauges which are considered for the loads monitoring. Moreover, each strain gauge which is depicted in Fig. 1(b) is applied not only at the front side, it is also applied on the backside. Hence, strain gauge position IV and V are applied as proposed by [3] to obtain the maximum strain in the post buckling regime as depicted in Fig.1(b). However, each single strain is measured in a quarter Wheatstone bridge to obtain the present strain changes at each position which provides the most information.

For the validation of the structural parameters, three different experiments were taken into account:

- (i) Measuring a tension strain at position IV and V to show that in a compressive loaded structure, in particular in the post-buckling regime, high tension stresses occur which causes a crack initiation in case of fatigue loading as proposed by [3].
- (ii) Loads and Usage Monitoring of the monitor structure is determined and recorded by strain gauges I and II.



(a) Load spectrum acting on the structure starting with 5 kN, 12.5 kN and 20 kN

(b) Measured strain at position IV and V on the front and backside in an undamaged state based on the load spectrum

Figure 3 : Experimental results of case (i)

- (iii) Measuring the strain redistribution in case of crack initiation and crack propagation. On the one hand to detect the crack and on the other hand to assess and possibly to estimate a prognosis for the identified damage at the proposed position V. Therefore, an artificial crack (1 cm distance to the strain gauge V, as depicted in Fig. 2 (b)) with a crack length of 3 cm was initiated. After that the plate was statically loaded up close to failure load (see Fig. 3 (a)) to measure the strain and stress behavior respectively next to the crack for different crack lengths and different loading. The crack propagation was simulated during the experiment by extending the crack artificially and the procedure was repeated up to a crack length of 6 cm with a discrete crack length of 1 cm per loop.

RESULTS AND DISCUSSION

case (i)

In case (i) we assumed a crack initiation for a compressive loaded structure based on the analytical results from [4] and the numerical results from [3]. As mentioned before in the post buckling regime high tension stresses occurs, caused by buckling deformation. Moreover, this bending stress can cause fatigue failure if the occurred tension stress is higher as the fatigue strength of the plate. For the assumed example in [3] the fatigue strength and the strain respectively is not allowed to be larger than the allowed strain ϵ_{all} (which means to avoid fatigue failure in this compressive loaded aluminum plate). In the first experiment the strain is measured at the proposed hot spots (position IV and V) to show a tension strain in a compressive loaded structure, see Fig. 3. A defined load spectrum is acting on the structure as depicted in Fig. 3 (a). After buckling tension strain on the structure can be observed. The failure load of this plate (failure load is achieved if the surface stress increases up to the yielding stress) is calculated in [3] with 22.6 kN.

As we can see from the result, there is a high tension stress acting on a compressive loaded structure, which did not achieve the allowable strain but which shows a high tension strain occurring on a compressive loaded structure. This tension stresses can cause fatigue failure.

case (ii)

The loads monitoring is based on the measured results from the strain gauges at position I and II to obtain the current load acting on the structure and to possibly track the stress redistribution in the post

buckling regime. The Loads Monitoring is done by determining the membrane strains

$$\epsilon_{\text{memb}}^{I,II} = \frac{\epsilon_{\text{top}}^{I,II} + \epsilon_{\text{bottom}}^{I,II}}{2}. \quad (1)$$

of the compressive loaded plate at position I and II. Therefore, the acting load can be determined by

$$F = E \epsilon_{\text{memb}}^{I,II} b t. \quad (2)$$

The result of this simple load reconstruction by measuring the membrane strains is depicted in Fig. 4 and is compared with the load introduced by the hydraulic testing cylinder. The load can be simple

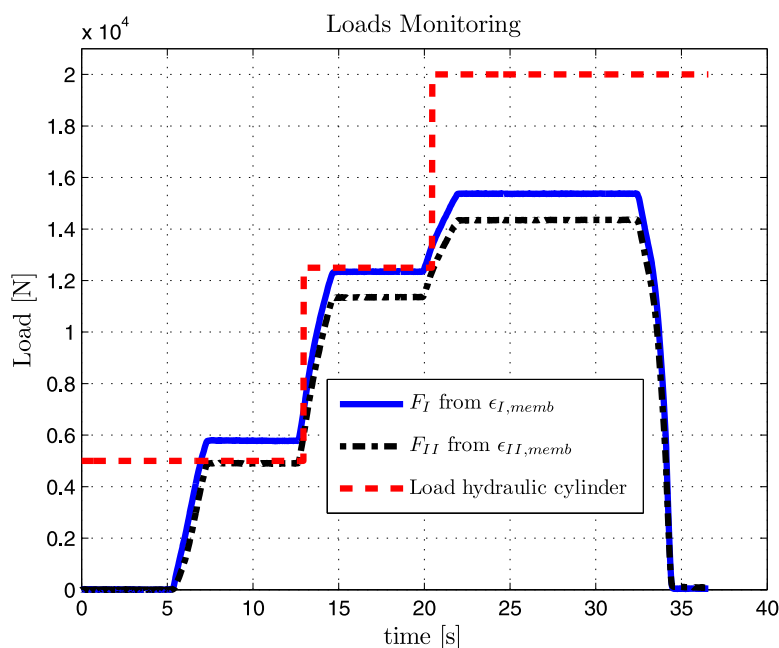


Figure 4 : Loads monitoring based on membrane strain measurement at position I and II compared with the loading from the hydraulic cylinder

measured by strain gauges in particular before buckling. In the post-buckling regime the load determined by Equation (2) is deriving from the real load due to strain redistribution to the stiff edges. To monitor the load with a simple strain measurement this post-buckling effects have to be considered by an assumed strain distribution in Equation (2).

case (iii)

In the last experiment the objective was to determine experimentally strain changes in case of a crack initiation and propagation with the mentioned considerations. The strain is measured at position IV and V on the front side (1) and backside (2) for the load spectrum as depicted in Fig. 3 (a). The idea within the SmartSHM approach is a simple data processing based on the information of a structural analysis. Due to uncertainties or other irregularities it is obvious that the crack started at the point with the highest tension strain which will be expected at position IV or V. In that case it is simple to compare the strains at position IV and V. Therefore, we take the mean value of each position. The mean strain of the strains at position IV on both sides as well as the mean strain of the strains at position V generated the curve in Fig. 5 and are known as membrane strains. The damage diagnosis procedure proposed within the SmartSHM approach is as follows:

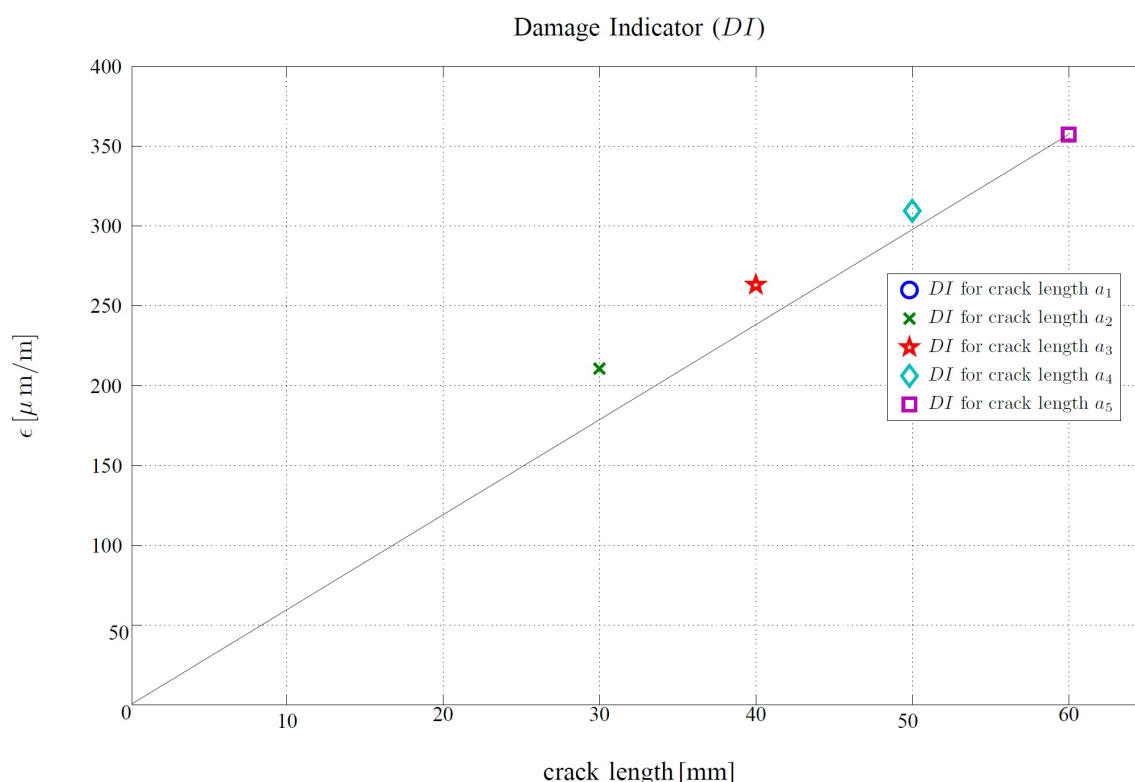


Figure 5 : Damage Indicator at a load of 5 kN

- Level 1 (detection): Damage indicator $DI \neq 0$
- Level 2 (localization): follows from the proposed strain gauges positions given in [3]
- Level 3 (qualification): is made already by the structural analysis which defined the optimal sensor network configuration
- Level 4 (quantification): can be assumed by analyzing the structure based on fracture mechanics (see conclusion)

The strains at positions IV and V should be identically as long as there is no damage. In that case a small difference between these two lines can be observed which is basically a deviation of the measurement issues, e. g. if the strain gauges are not bonded exactly on the same positions. As mentioned before, in case of no damage these two strain values should be identically. For data processing simplification we propose to take the difference between these two values which emphasizes sensitive damage indicator (DI) for the compressive loaded structure. As long as there is no difference between the strains at position IV and V, we obtain (more or less) a line close to zero, see Fig.3 (b). As no data has to be sent in the undamaged case the SmartSHM approach reduces the amount of data and transmission energy. Furthermore, it indicates more significantly if there is a damage or not compared to the information we obtained only from the mean values.

However, if we initiate a crack with a length of 30 mm as depicted in Fig.1 (b) and we measure again the strains at position IV and V we obtain a damage indicator which clearly identifies a significant structural change. In Fig. 5 an increasing of the crack length shows a significant change of the damage indicator which simply detects the damage. Damage assessment can be performed by setting a critical level for the damage indicator.

CONCLUSION

The experimental investigation of a compressive loaded structure within the novel SHC approach resulted in the following:

- (a) A critical tensile strain can be monitored for compressive loaded structures which generates cracks in case of fatigue loading in the post-buckling regime
- (b) Loads and usage monitoring: With the simple strain evaluation approach the loads monitoring works only in the linear elastic regime. A loads monitoring in the post-buckling regime requires a more complex assumption of the strain distribution.
- (c) The experimental validation to identify a damage within the SmartSHM approach based on a structural analysis to use simple measurement devices and data processing procedures was discussed. The information from the structural analysis simplifies the damage identification process significantly. The crack in the plate could be clearly identified as well as a crack propagation was clearly measurable by using simple strain gauges.

For future work this experimental data can be used to assess the identified damage as well as estimate a damage prognosis to carry on to validate other modules within the superior SHC approach. Furthermore, more investigations have to be done on composite material, in particular on the damages caused by defects and how can we handle this damages within the SHC approach.

ACKNOWLEDGMENT

The financial support by the Austrian Federal Ministry of Economy, Family and Youth and the National Foundation for Research, Technology and Development is gratefully acknowledged.

REFERENCES

- [1] C. Boller, F. K. Chang, and Y. Fujino. *Encyclopedia of Structural Health Monitoring*. Wiley, 2009.
- [2] C. Viechtbauer, K. U. Schröder, and M. Schagerl. Structural Health Control - A Comprehensive Concept for Observation and Assessment of Damages. *The 13th Mechatronics Forum International Conference Proceedings*, 2:599–603, September 2012.
- [3] K. U. Schröder, C. Viechtbauer, and M. Schagerl. Identification and monitoring of structural parameters as damage indicators for plates in the post-buckling regime. *Structural Health Monitoring 2013 - A Roadmap to Intelligent Structures*, 1:1137–1143, September 2013.
- [4] M. Schagerl. On the magnitude of surface stresses of buckled plates. *Proceedings of Applied Mathematics and Mechanics*, 11:269–270, September 2011.