Predicting the Lifetime of the PCB - From Experiment to Simulation

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Abstract

Two major drivers in electronic industry are electrical and mechanical miniaturization. Both induce major changes in the material selection as well as in the design. Nevertheless, the mechanical and thermal reliability of a Printed Circuit Board (PCB) has to remain at the same high level or even increase (e.g. multiple lead-free soldering). To achieve these reliability targets, extensive testing has to be done with bare PCB as well as assembled PCB. These tests are time consuming and cost intensive. The PCBs have to be produced, assembled, tested and finally a detailed failure analysis is required to be performed.

This paper examines the development of our concept and has the potential to enable the prediction of the lifetime of the PCB using accelerated testing methods and finite element simulations.

The method of evaluation for the developed concept uses the mechanical loading (drop test) on Printed Circuit Board Assembly (PCBA) test vehicles.

The aim of this study is to show, that experiments on material specimen level in combination with corresponding simulation models, allow a significant reduction of previously required board level tests. Doing so characteristic failure curves, correlating simulated local failure parameters to measured lifetimes, were generated and used to predict the performance of unknown PCB types. Applied tools, in order to determine relevant local failure parameters, were based on fracture mechanics concepts, as e.g. X-FEM and contour integral simulations.

This research was carried out by Austria Technologie & Systemtechnik AG (AT&S AG) in cooperation with the Polymer Competence Center Leoben (PCCL).

Introduction

Increasing reliability or maintaining same reliability level with enhanced design rules, is one of the major scopes in the PCB industry. Driven by the trend of electrical miniaturization, not only line and spaces are getting smaller, but according build ups are also requiring thinner dielectric materials. As there is not so much information available, extensive testing is needed to check the level of reliability. One of these well-known tests is the standardized Board Level Drop Test (BLDT). This mechanical shock test is intended to determine the compatibility of components to withstand moderately shocks as a result of suddenly applied forces or abrupt changes in motion produced by handling, transportation or field operation. These dropping events cannot only cause mechanical failures in the component or solder joint, but also cause cracks in the micro-via or dielectric layer of the PCB (see Fig. 1).

Crack in solder (Type I) | Crack in via structure (Type II) | Crack in dielectric layer (Type III)

Fig. 1 - Different types of failure modes

The BLDT is a very cost and time intensive test. Printed circuit boards have to be manufactured and assembled with daisy chain components. Then, the Drop Test is done according the specification (up to 1000 drops) and afterwards, a very accurate and time consuming failure analysis is carried out. All in all, one Drop Test lasts 60-70hours and costs €9000-€10000. And this is only for one set-up.

Therefore, the idea was born to develop a methodology to determine parameters for failure caused by mechanical shock and furthermore to simulate the BLDT – and necessary complementary experiments could be reduced.

Test vehicle and materials

The used test vehicle is based on the JEDEC JESD 22-B111 comprising a footprint of a daisy chain level 2 components with following specification:

- Package size 12x12x0,86mm
- 288 I/O
- Die size: 10x10mm
- 0,5mm pitch
- LF35 solder ball

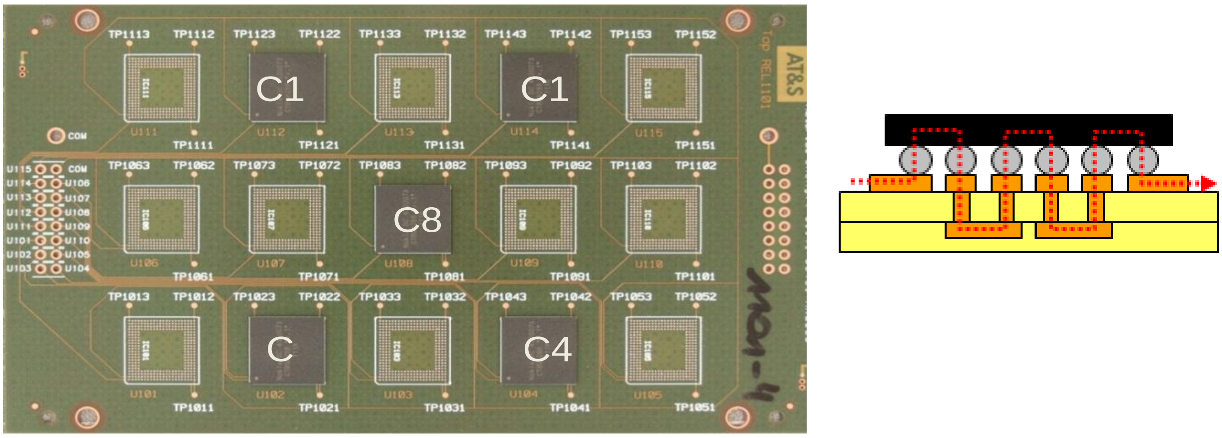
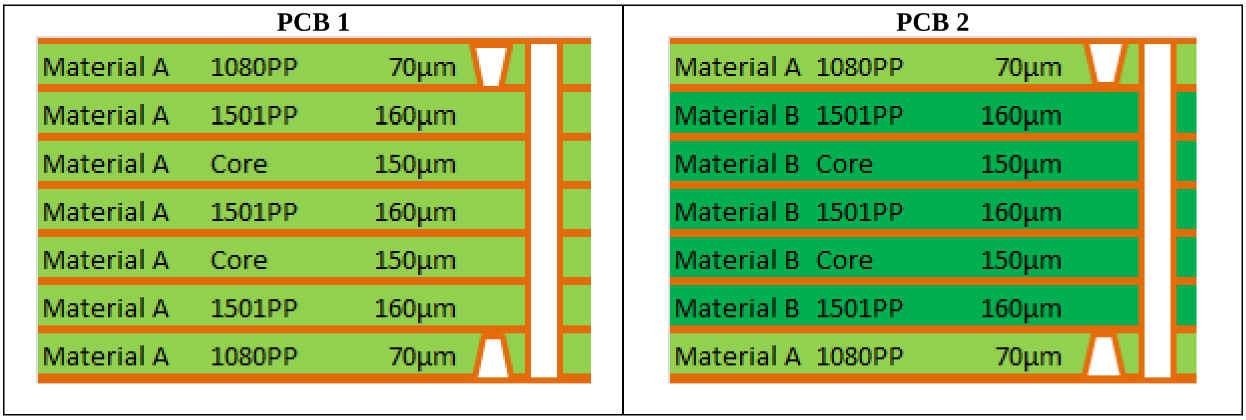


Fig. 2 - JEDEC Test Board with assembled components

The five center components were chosen to be assembled due to overall higher exposure to tension during this type of drop test, as these particular areas of the test vehicle deviate farthest from a neutral axis (see

Fig. **2**).

The build (shown in Fig. 3) for the 1,0mm thick PCB was an 8 layer multi-layer. All materials used were halogen-free materials. The materials for the center layers contained same resin matrix, but different types of fillers (Material A and Material B), whereas the same type of material (Material A) was used for the outermost layer on PCB 1 as well as on PCB 2.



PCB 1			PCB 2		
Material A	1080PP	70µm	Material A	1080PP	70µm
Material A	1501PP	160µm	Material B	1501PP	160µm
Material A	Core	150µm	Material B	Core	150µm
Material A	1501PP	160µm	Material B	1501PP	160µm
Material A	Core	150µm	Material B	Core	150µm
Material A	1501PP	160µm	Material B	1501PP	160µm
Material A	1080PP	70µm	Material A	1080PP	70µm

Fig. 3 - Stack Up

The Prepregs were reinforced with glass fiber woven fabrics (Fig. 4) corresponding to the IPC standard (IPC-4412A 2006). Due to the reinforcement the direction dependent material properties had to be considered. However, due to the defined 0° and 90° fiber orientations orthotropic behavior instead of general anisotropy could be presumed.

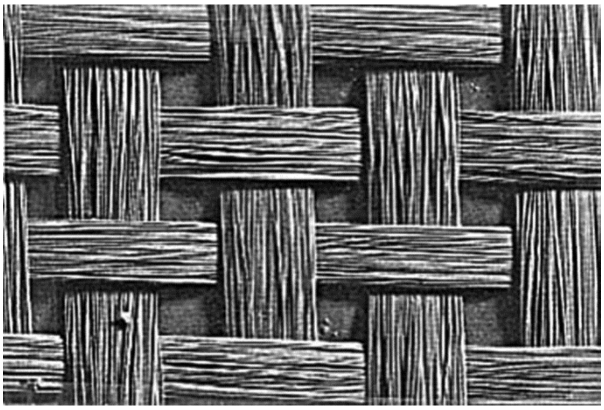


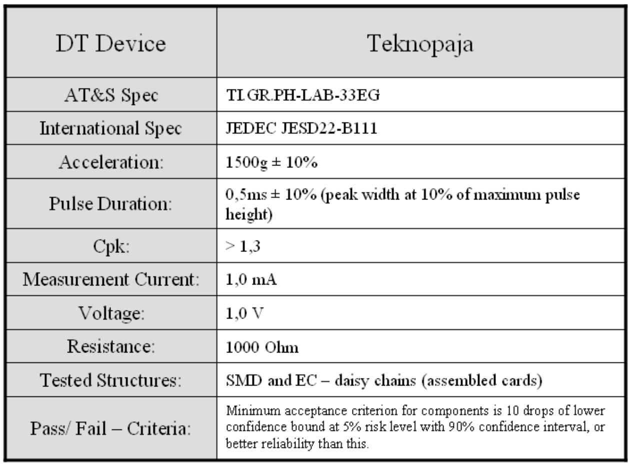
Fig. 4 - Typical micro section (50x) of woven glass fabric (Jawitz, Jawitz 2007)

Experimental

Board Level Drop Test (BLDT)

The Drop Test specification is based on the JEDEC JESD22-B111 (JEDEC STANDARD JESD22-B111) Board Level Drop Test (BLDT). Test vehicles are soldered at the test terminal PTHs and test events were monitored online as opposed to post hoc testing and verification.

The PCBs are mounted with the assembled side facing down on the drop tester. Nine samples have to be dropped: one for first failure (=weakest link) analysis and the other 8 for cumulative. The first failure test has to be stopped after the first failure. The cumulative tests end, when all relevant components failed or after 1000 drops. After completion, measure the final resistance of all tested components and make pictures of the samples (see Fig. 5).



DT Device	Teknopaja
AT&S Spec	TI.GR.PH-LAB-33EG
International Spec	JEDEC JESD22-B111
Acceleration:	1500g ± 10%
Pulse Duration:	0,5ms ± 10% (peak width at 10% of maximum pulse height)
Cpk:	> 1,3
Measurement Current:	1,0 mA
Voltage:	1,0 V
Resistance:	1000 Ohm
Tested Structures:	SMD and EC – daisy chains (assembled cards)
Pass/ Fail – Criteria:	Minimum acceptance criterion for components is 10 drops of lower confidence bound at 5% risk level with 90% confidence interval, or better reliability than this.

Fig. 5 - Board Level Drop Test Set-Up and Specification

Board Level Cyclic Bend Test (BLCBT)

According to a previous work (Fuchs, Major 2011) the Board Level Cyclic Bend Test (BLCBT) is considered representative of BLDT behavior. In Fig. 6 a schematic comparison is presented.

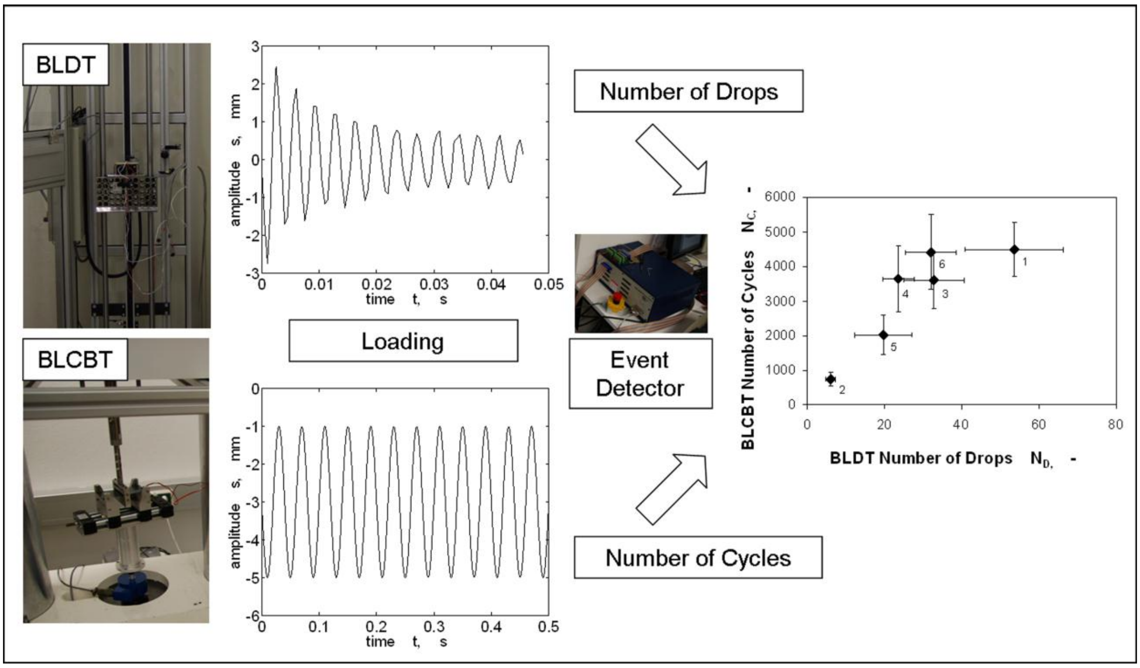


Fig. 6 - Comparison of the Board Level Drop Test (BLDT) and the Board Level Cyclic Bend Test (BLCBT) (Fuchs, Major 2011)

In the BLCBT the same test vehicles, failure detection methodology and failure criteria, than in the BLDT, are used, but instead of discontinuous drops a continuous sinusoidal bending load is applied. However, due to the advantages over the BLDT, e.g. that it

- is faster to perform,
- can be simulated at lower computing times in a finite element model,
- and can easily be adapted to different load levels,

the reliability estimations presented in this work were based on experiments and simulations of the BLCBT. The BLCBT set-up is shown in Fig. 7.

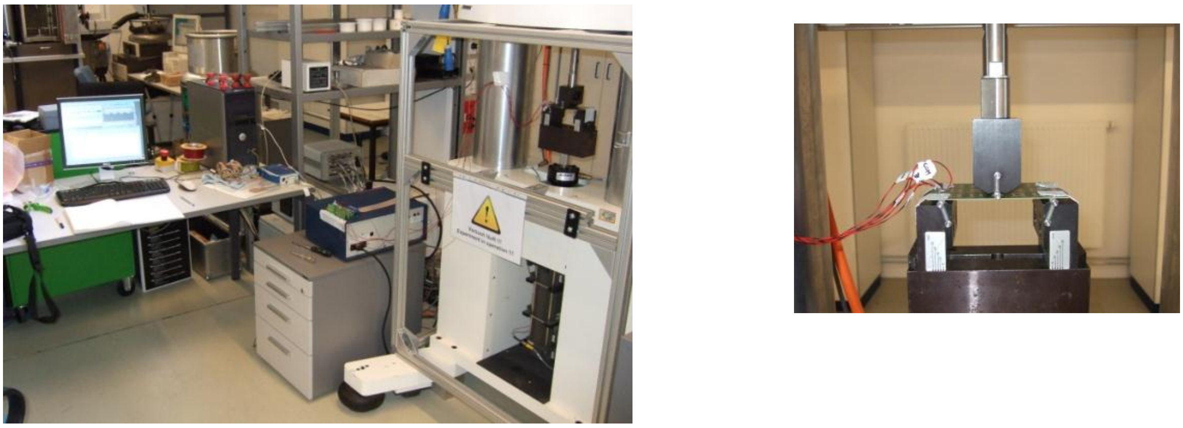


Fig. 7 - Board Level Cyclic Bend Test Set-Up

Further experiments were performed on specimen level in order to determine the behavior of different materials applied in the test vehicle. The behavior of the individual layers of the PCB had to be known, as it was crucial for the local stress concentration simulations.

In order to determine the basic engineering constants tensile tests, featuring a digital image correlation system (Fig. 8), were applied. However, the fiber reinforced insulating layers showed, due to the 0°/90° glass fiber woven fabrics, an orthotropic behavior. Thus a combination of both, direction dependent experiments and a micromechanics approach based on a mean-field theory were applied to determine the material properties. The in plane properties were determined performing tensile test in the 0°, 90 ° and 45° direction, while the out of plane parameters were calculated using a reverse engineering method. Thereby the matrix properties were back calculated from the in plane composite properties and applied to determine the out of plane parameters using the software Digimat (digmat-MF 4.2.1, e-Xstream engineering SA, Louvain-la-Nèuve, BE). Furthermore, for the layers with a regular copper structure a homogenized material law was determined using a representative volume element method. The applied methods are explained in more detail in Fuchs et al. 2012.

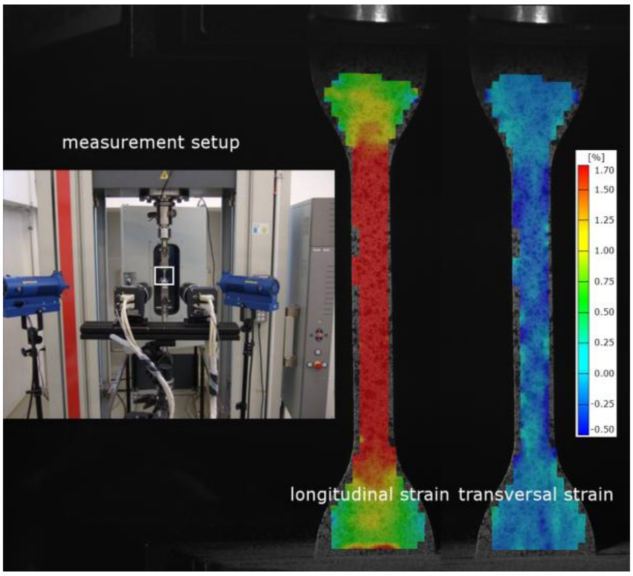


Fig. 8 - Tensile test set-up including a digital image correlation system to determine the longitudinal and transversal strain field

Next to the basic engineering constants a cohesive zone model was determined in order to be able to describe the fracture process in the dielectric layers in the simulation. The determined parameters were based on double cantilever beam tests and corresponding simulations of the Prepregs.

Simulation

Using finite element method software (Abaqus 6.11, Simulia, Daussault Systèmes, Providence, RI, USA) a simulation model of the BLCBT was generated. In order to determine the local stress situation, a submodeling technique, using the results of a global model to apply the boundary conditions on a local submodel, was applied. Thus, it was possible to use a rough mesh to simulate the global deformation and a dense mesh to analyze the local situation in detail, while keeping the computation times low. The solder ball carrying the highest loads according to the global model results was chosen for the local model. Both, the global model and the submodel are shown in Fig. 9.

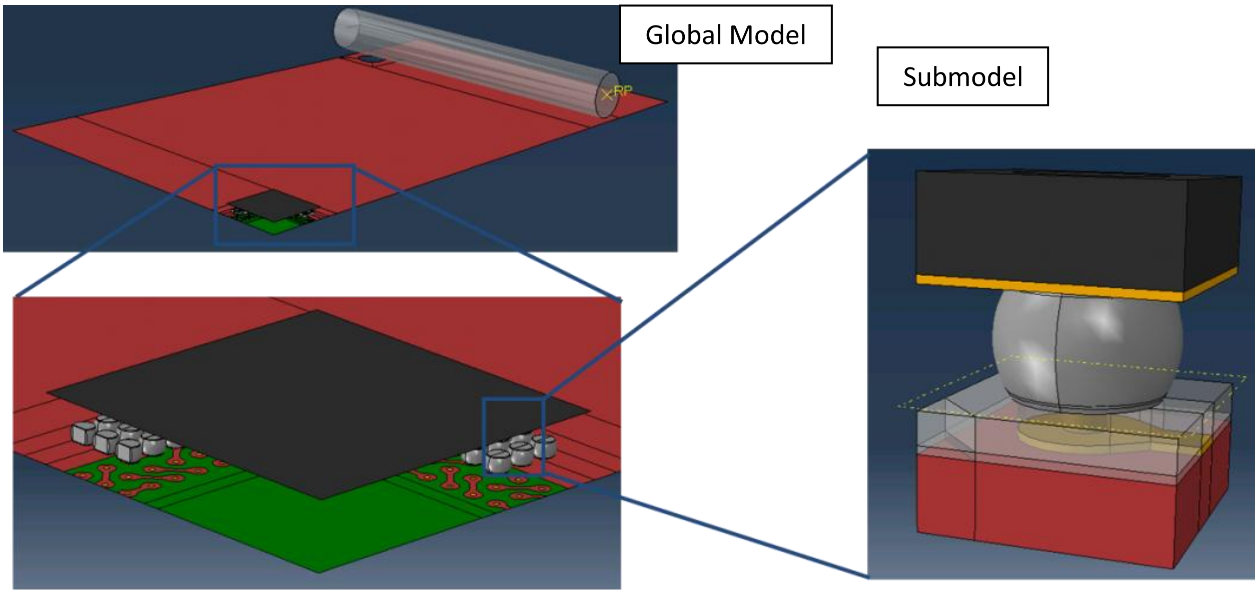


Fig. 9 - Global and local simulation model

The results of the sub model allowed the evaluation of the local stress situation and thus the determination of a representative loading situation parameter for most failure modes. However, for the failure mode, where a crack starts at the corner between solder ball and outermost dielectric layer (Type III in Fig. 1) a stress evaluation was not sufficient, as the crack initiates at a sharp reentrant edge and the simulated stress value strongly depends on the chosen mesh size. Thus a fracture mechanics approach was applied. Therefore, in a further submodel, in a first step the crack initiation was calculated using an extended finite element method simulation based on the determined cohesive zone law. Knowing how and where the crack initiates, a contour integral simulation could be used to determine the effective J-Integral value. The J-Integral could then be used to evaluate the loading situation for failure type III. Thus, using the submodel simulation models it was possible to determine failure mode dependent parameters which could be considered representative of the local loading situation.

Results and Outlook

To verify the fracture simulation the crack determined in the simulation model was compared to the failure pattern observed in the experiments. A defined board was tested in a BLCBT till first failure was detected. The failed board was examined and cross sections of the solder balls were prepared and analyzed using light microscopy. In Fig. 10 a typical cross section featuring a crack starting at the edge between solder ball and outermost epoxy matrix is shown. Additionally, the initial crack path predicted by the simulation model is presented. The predicted and experimentally observed crack showed a very good agreement.

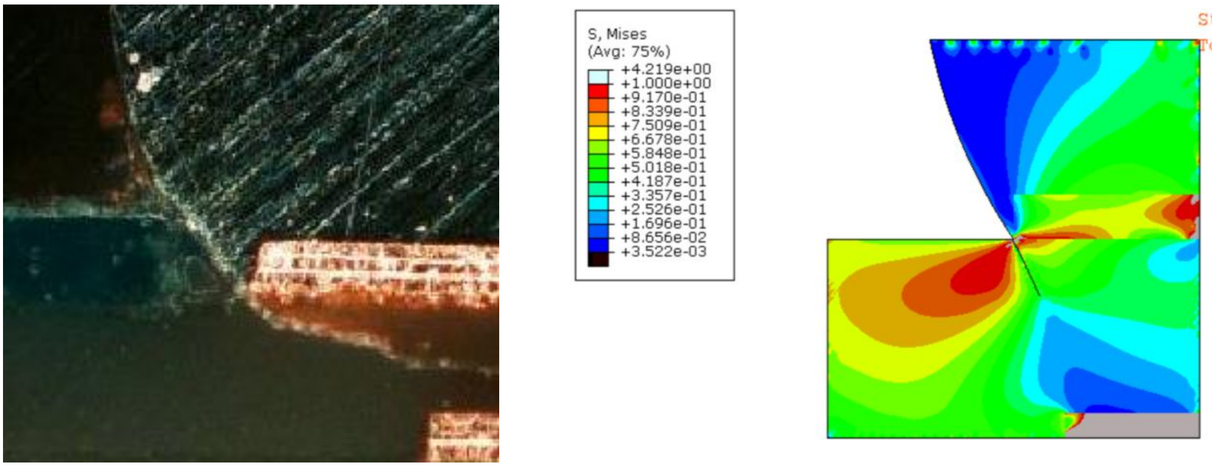


Fig. 10 - Comparison of the failure pattern of a board failed in a BLCBT for simulation and experiment

Based on this results contour integral simulations of two submodels based on different global PCB stack ups – the filler material of the inner dielectric layers was varied - were performed. The simulation results showed a significant influence of the different materials used. The first simulation lead to a J-Integral value of 163 J/m^2 (PCB 1) while the second simulation, taking into account a stiffer matrix material for the inner layers, lead to 193 J/m^2 (PCB 2). However, these results have not been verified by BLCBT experiments yet, but they demonstrate a possible approach to compare different stack ups and designs with respect to their influence on failure type III.

In future work, a lifetime prediction approach, applied already for failure type I in (Fuchs et al.), will be used to evaluate the possibility to predict the failure Type III reliability performance of PCBs. The approach is presented schematically in Fig. 11. BLCBT are performed at different amplitude levels and corresponding local loading situation and simulations are performed to generate a characteristic failure curve for the specific failure types. Thereby the simulated local loading parameters are plotted over the measured cycles to failure. This curve again can be used to predict the cycles to failure of e.g. unknown PCB stack ups only by simulating the changed local loading parameters.

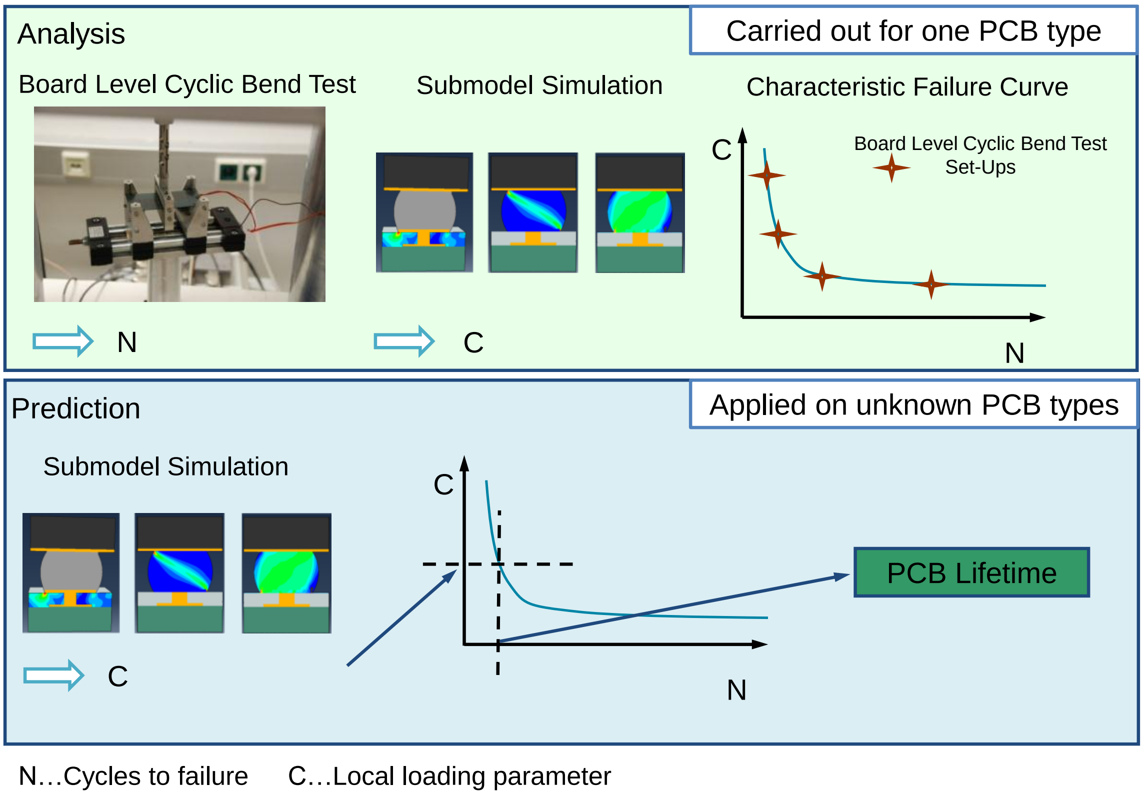


Fig. 11 - Schematic Representation of the lifetime prediction methodology (Fuchs 2012)

Summary and Conclusion

The initial task at hand was to evaluate a concept to predict the lifetime of PCBs by creating a simulation model.

We found a correlation between the Board Level Drop Test and the Board Level Cycling Bend Test. Therefore, the BLDT can be replaced and the BLCBT can be used as Quick Test to check new materials.

The in-plane material data of the individual glass reinforced layers was experimentally determined, while the out-of-plane data (orthotropic behavior had to be taken into account) was determined using a micromechanics approach (digimat –MF, e-Xstream engineering SA, Louvain-la-Neuve, BE).

For the determination of the local loading situation parameter on the outermost PCB layer a simulation model based on a submodeling technique was applied. Additionally, it was necessary to use a fracture mechanics based model in order to determine a mesh size independent value to evaluate this loading situation. The combination of BLCBT at different amplitudes and the local loading simulations will allow the generation of characteristic failure curves. Based on these characteristic failure curves, a possible lifetime prediction methodology was suggested. Further scope of investigation on this topic may include involving further failure modes caused by Drop Test. After a successful verification and implementation of this methodology, the cost and time consuming Drop Test experiments might be significantly reduced.

Furthermore, this methodology could be used for other widely used reliability tests as well, e.g. Temperature Cycle Tests.

References

IPC-4412A. Specification for Finished Fabric Woven from "E" Glass for Printed Boards (2006).

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Fuchs, P.F; Major, Z. (2011): Cyclic bend tests for the reliability evaluation of printed circuit boards under dynamic loads. In Frattura ed Integrità Strutturale (15), pp. 64–73.

Fuchs, P.F; Pinter, G.; Tonjec, M. (2012): Determination of the orthotropic material properties of individual layers of printed circuit boards. In Microelectronics Reliability 52 (11), pp. 2723–2730.

Fuchs, P. F. (2012): Characterization and Simulation of the Deformation and Failure Behavior of Electronic Components. Dissertation. MontanUniversität Leoben, Leoben. Werkstoffkunde und Prüfung der Kunststoffe.

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JEDEC STANDARD JESD22-B111, July 2003: Board Level Drop Test Method of Components for Handheld Electronic Products.

Predicting the Lifetime of PCB

From Experiment to Simulation

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PCCL
Polymer Competence Center Leoben

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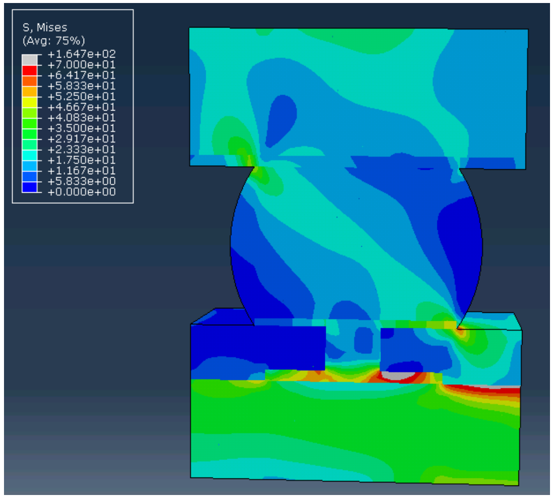
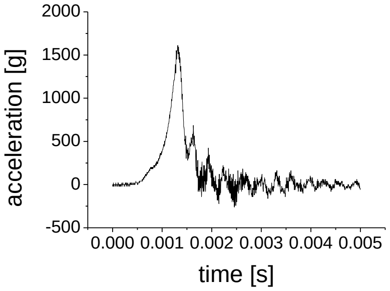
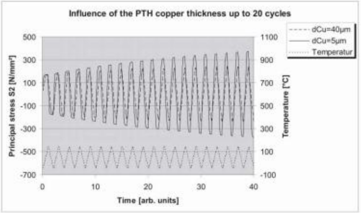


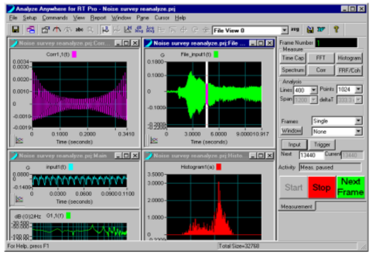
Loadings on PCB



Mechanical Shock



Temperature



Analyze Anywhere for RT Pro - Noise survey reanalyze.prj

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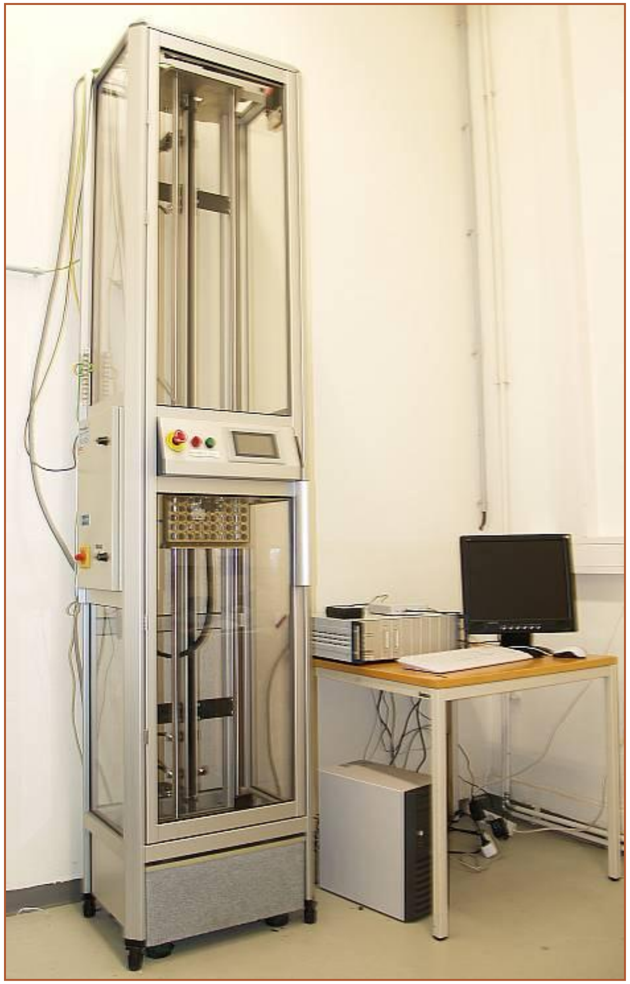
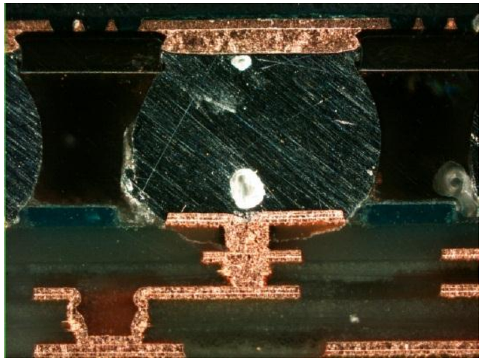
Vibration

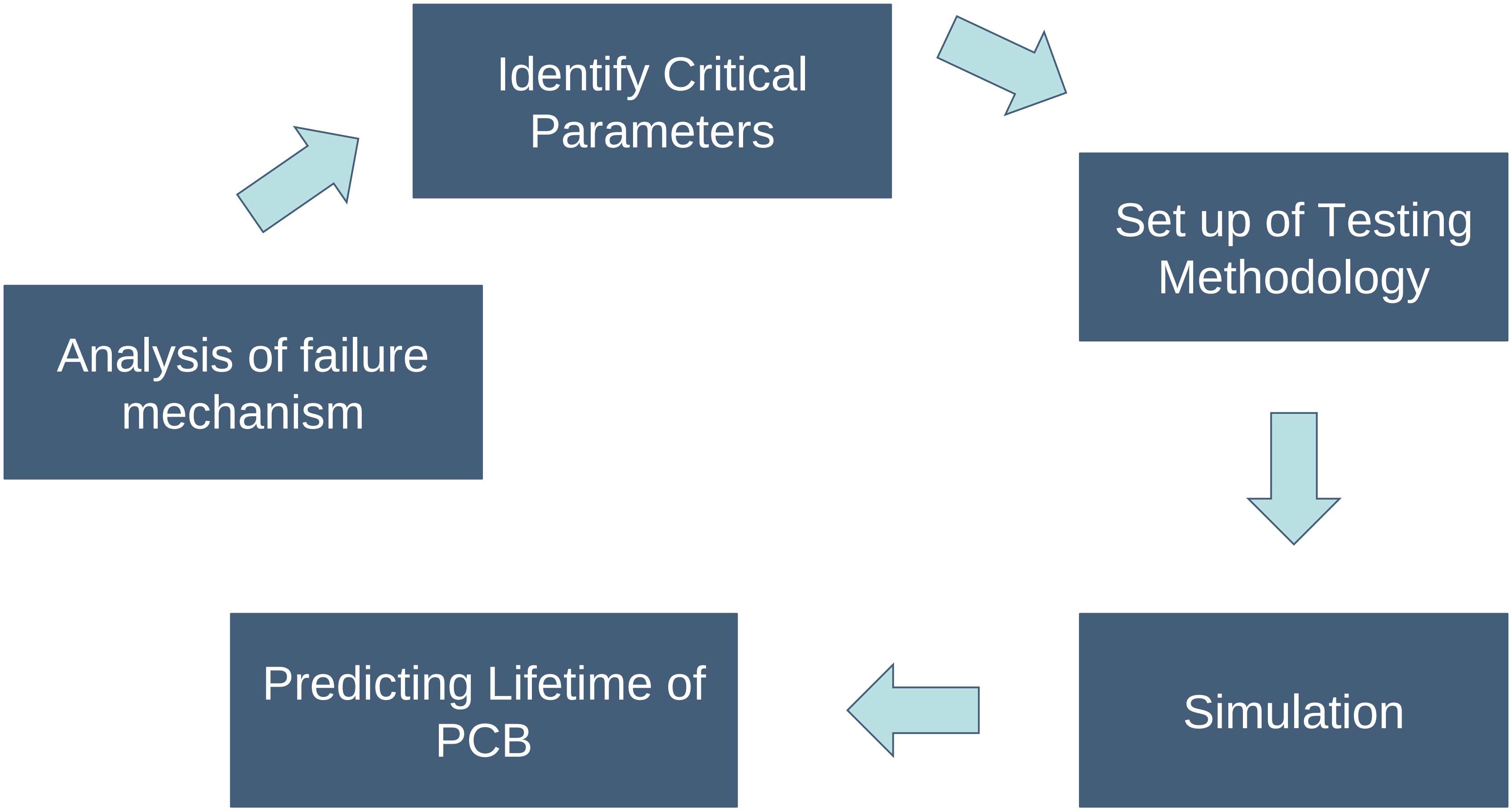
Board Level Drop Test (BLDT)



- Time: 60-70hrs
- Cost:
  - Components 300€
  - Assembly: 2700€
  - Testing and Analysis: 6500€



Concept



Identify Critical Parameters

Set up of Testing Methodology

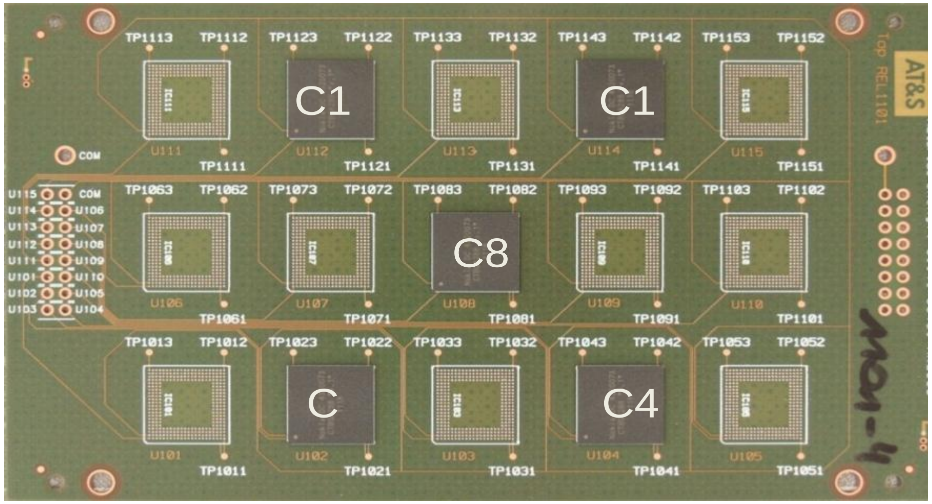
Simulation

Predicting Lifetime of PCB

Analysis of failure mechanism

Test Vehicle

JEDEC STANDARD JESD22-B111



- Package size 12x12x0,86mm
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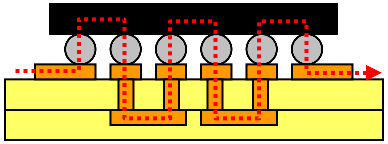
- Die size: 10x10mm
- 0,5mm pitch
- LF35 solder ball

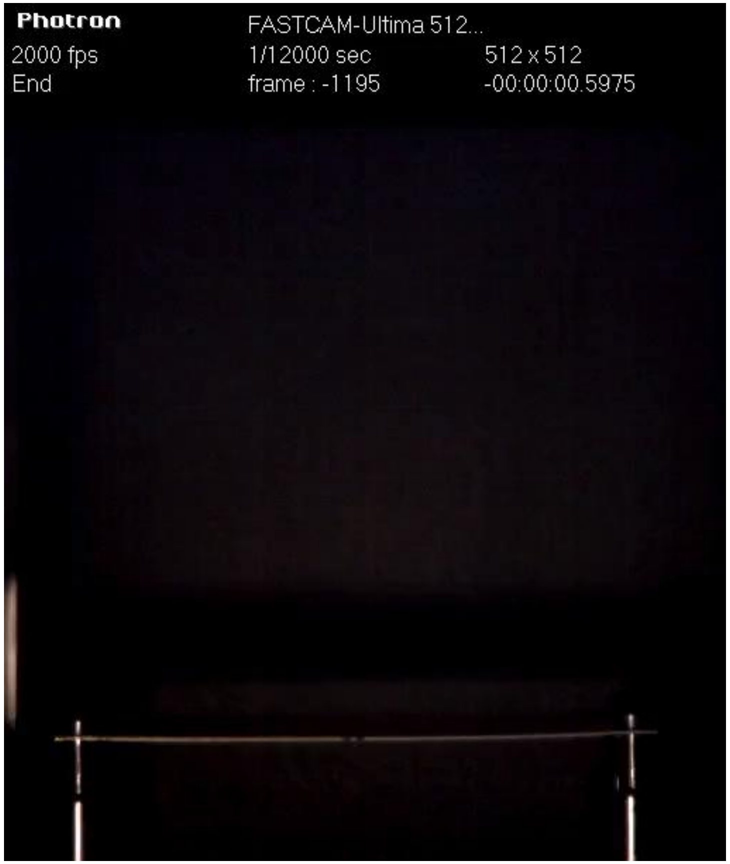


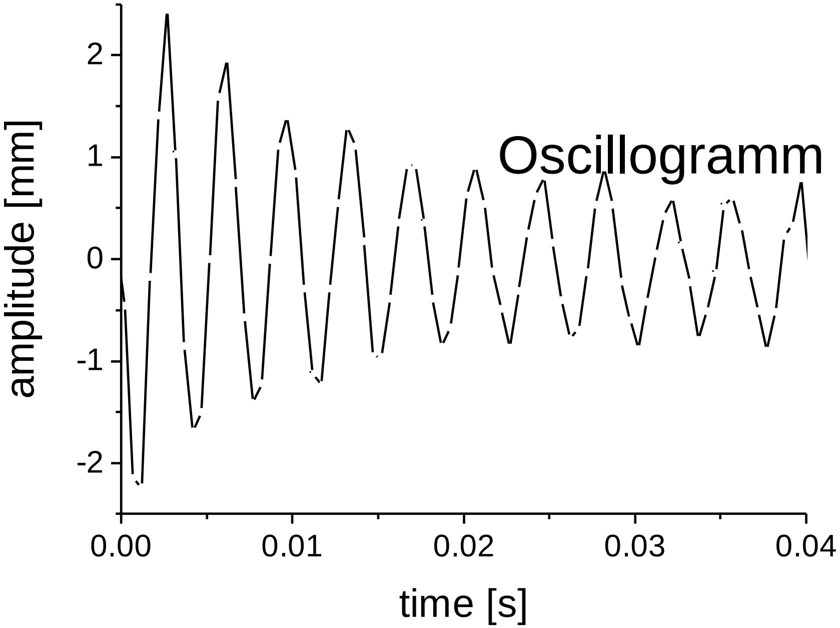
Material A	1080PP	70µm
Material A	1501PP	160µm
Material A	Core	150µm
Material A	1501PP	160µm
Material A	Core	150µm
Material A	1501PP	160µm
Material A	1080PP	70µm

Material A	1080PP	70µm
Material B	1501PP	160µm
Material B	Core	150µm
Material B	1501PP	160µm
Material B	Core	150µm
Material B	1501PP	160µm
Material A	1080PP	70µm

- 8 Layer Multi-layer, 1mm
- Halogen-reduced material
- Different types of fillers

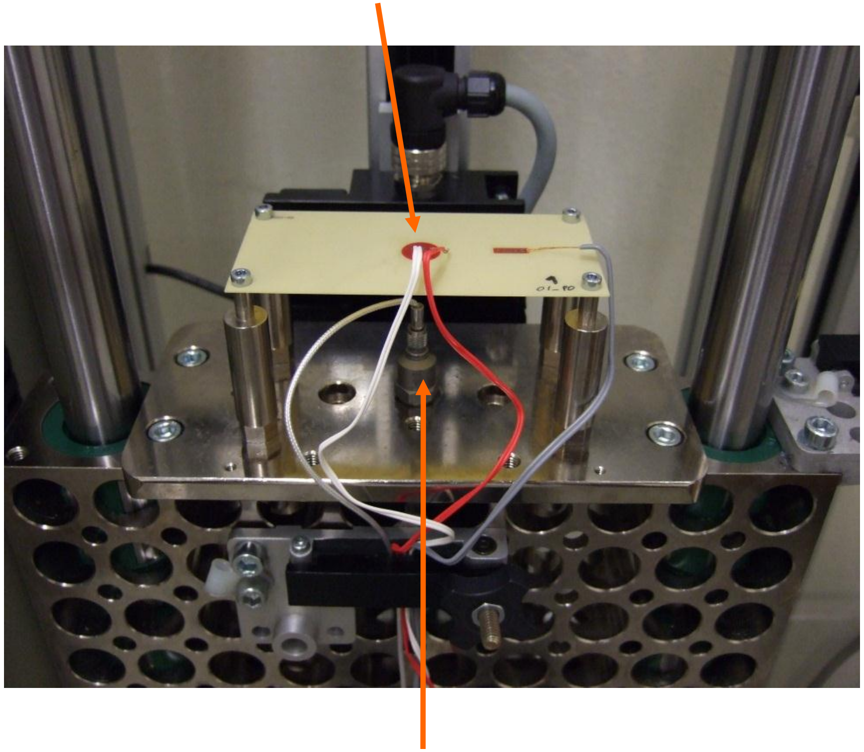
Analysis of BLDT





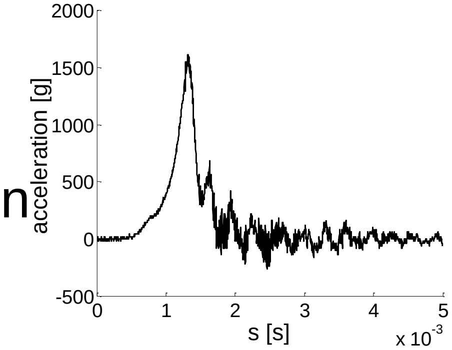
Load and Deformation Measurement

Strain Gauges

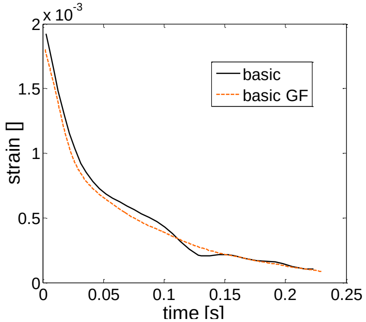


Acceleration Sensor

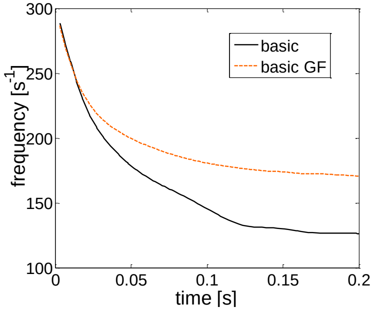
Acceleration Signal



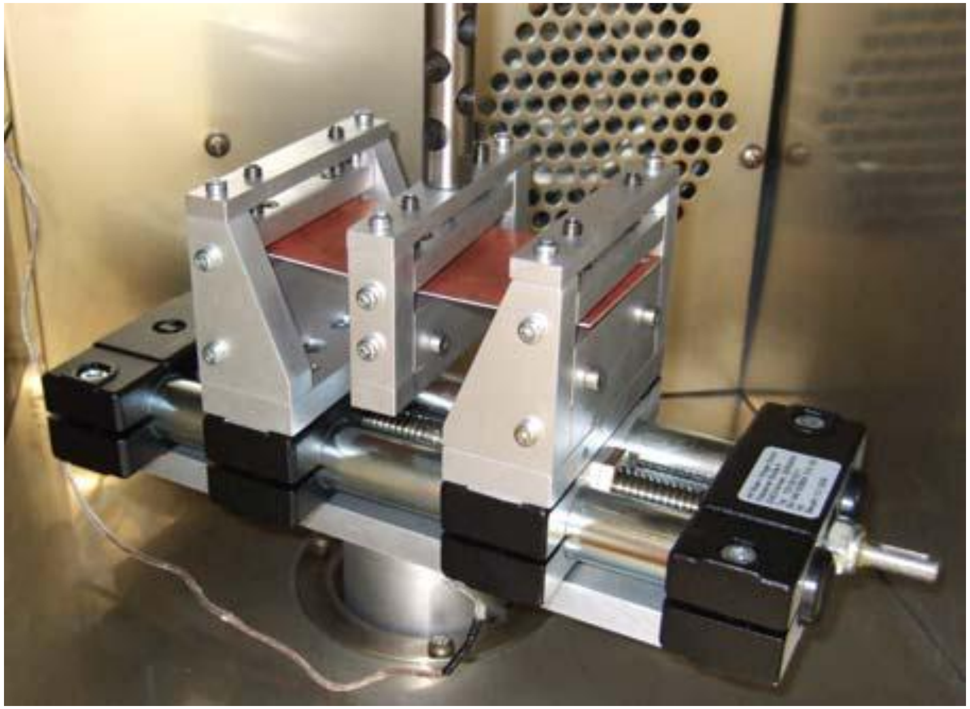
Strain Envelope



Frequency Development



Test Set Up for BLCBT

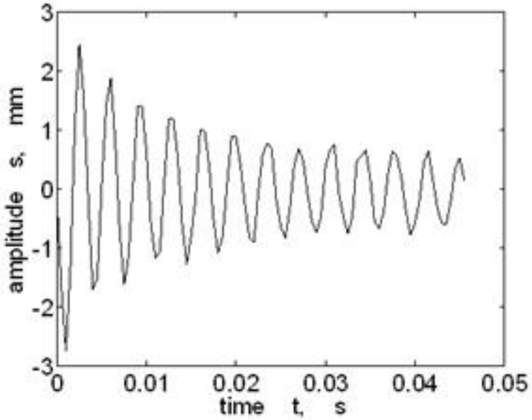


Electrodynamic Testing Machine

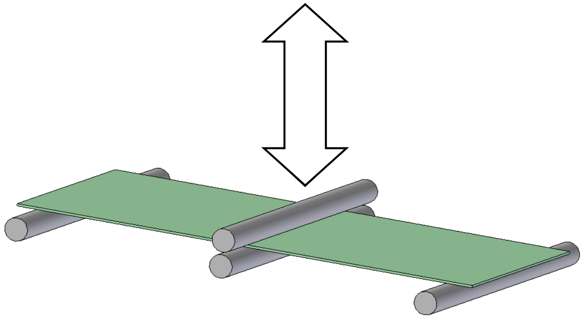
BOSE 3450, BOSE Co, MN, USA

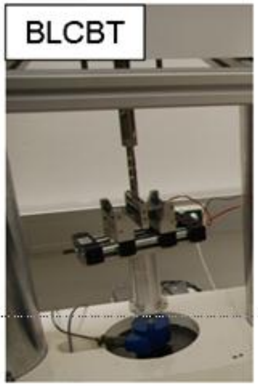
Bending Fixture

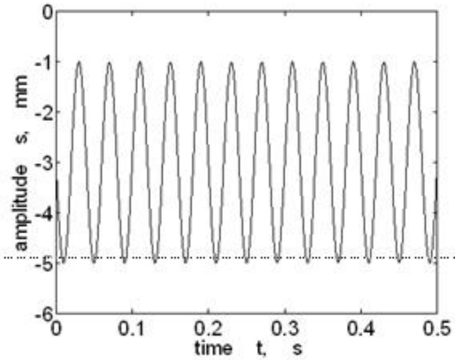
Replacement of DT

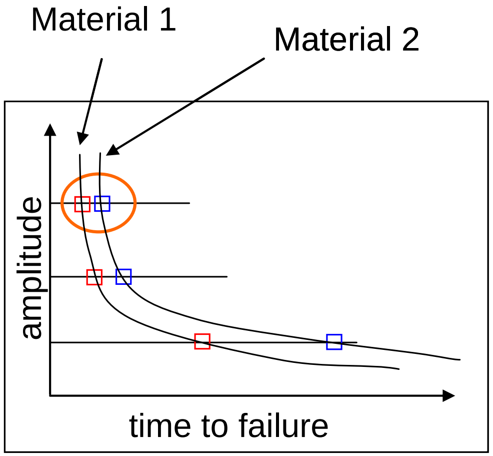


3 Point Bending Fixture



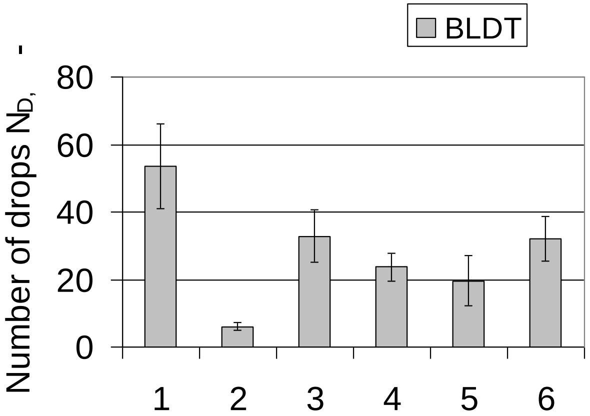


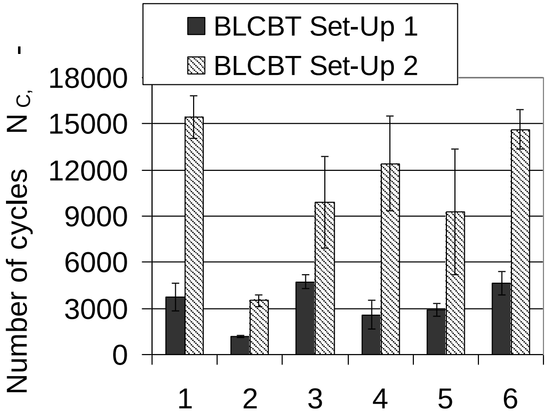




Characteristic Failure Curves

Replacement of DT





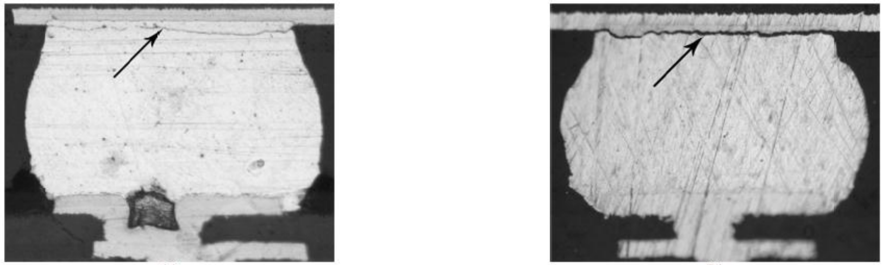

(a) (b)

Figure 11: Comparison of a) the failure of design 1 in the BLDT and b) the failure of design 1 in the BLCBT, analyzed with light microscopy.

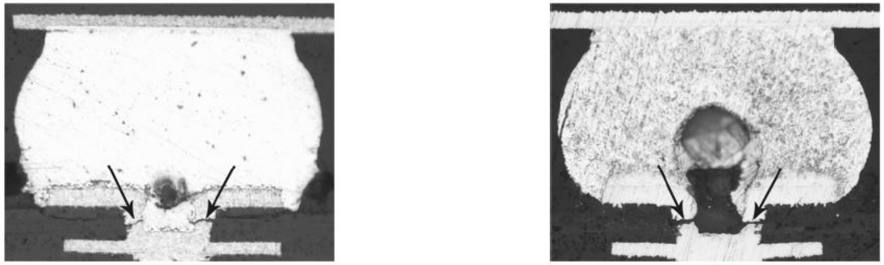
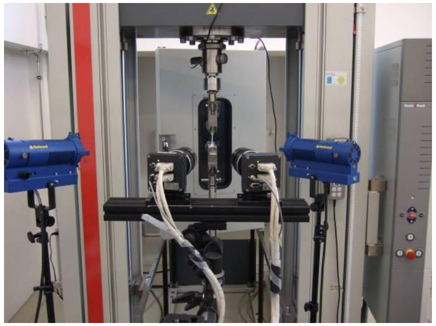

(a) (b)

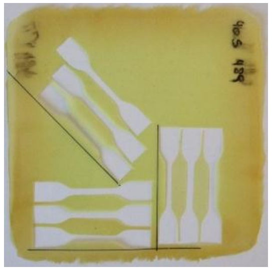
Figure 12: Comparison of a) the failure of design 2 in the BLDT and b) the failure of design 2 in the BLCBT, analyzed with light microscopy.

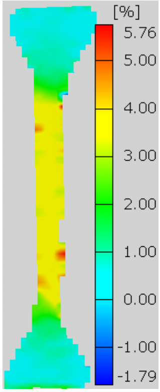
Comparison Board Level Drop Test (BLDT) and Board Level Cyclic Bend Test (BLCBT)

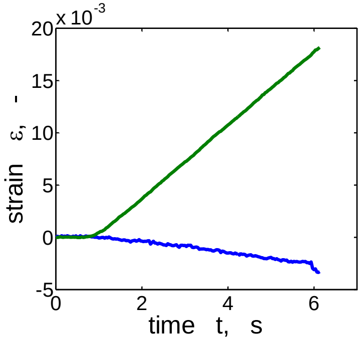
Orthotropic Material Behavior

E11, E22 and ν12 could be determined directly by the measurements



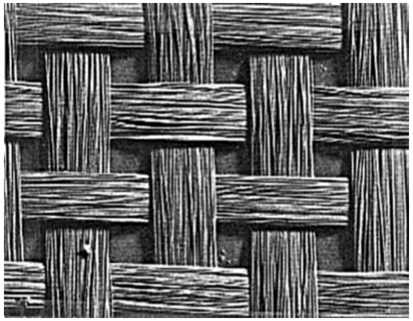






G12 could be calculated from the 45 ° tensile tests

$$G_{12} = \frac{E45 \cdot E11 \cdot E22}{4 \cdot E11 \cdot E22 - E45 \cdot \left[E22 + 2 \cdot \nu 12 \cdot E22 - E11\right]}$$



Digimat Simulation

E33, n13, n23, G13 and G23 are not experimentally determinable

Composite

E11, E22, ν12 are determined in experiments

resin content (producer data sheet)

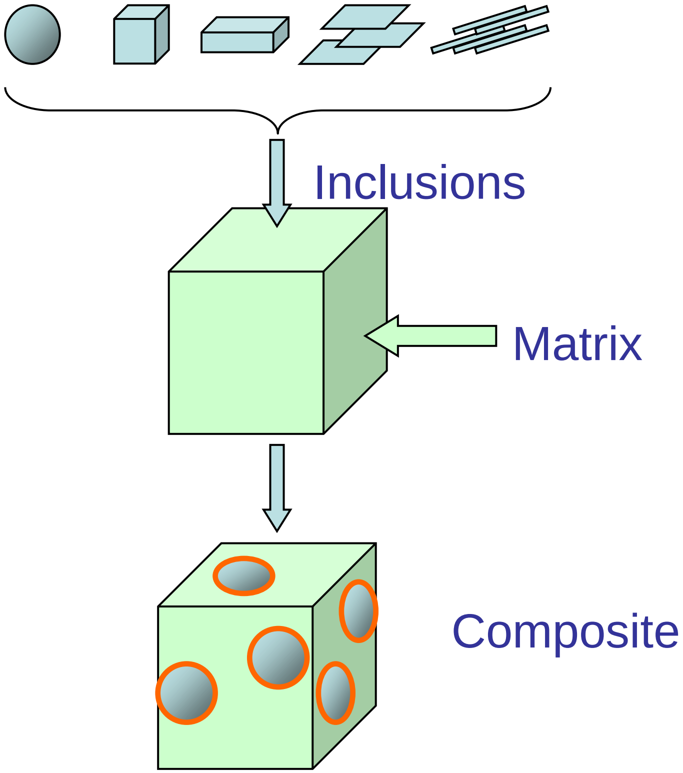
Inclusions

E-Glass properties (literature)

Matrix

Reverse calculation of the matrix properties

⇨ Determination of Composite E33



Digimat Simulation

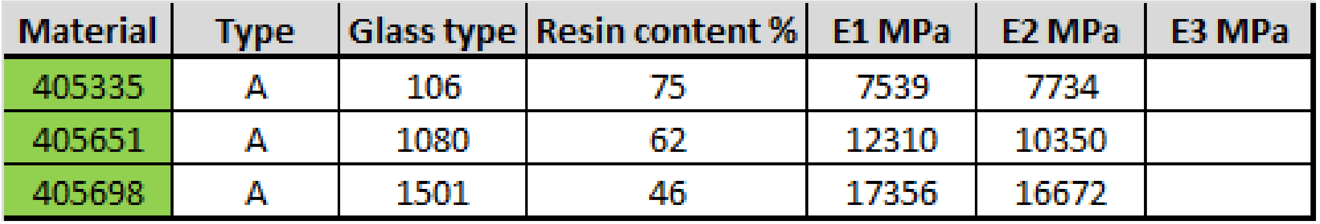
- Matrix Material A – Measured Values

  E= 7150 MPa, ν =0.35 and ρ= 1.6 g/cm^3

- Glass-properties - Literature

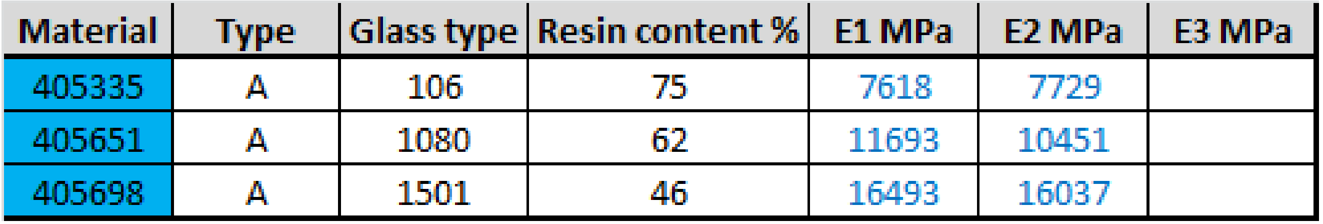
  E=73000 MPa, ν =0.2 and ρ= 2.6 g/cm^3

- Resin Content 75%



Material	Type	Glass type	Resin content %	E1 MPa	E2 MPa	E3 MPa
405335	A	106	75	7539	7734	
405651	A	1080	62	12310	10350	
405698	A	1501	46	17356	16672	

Measurement



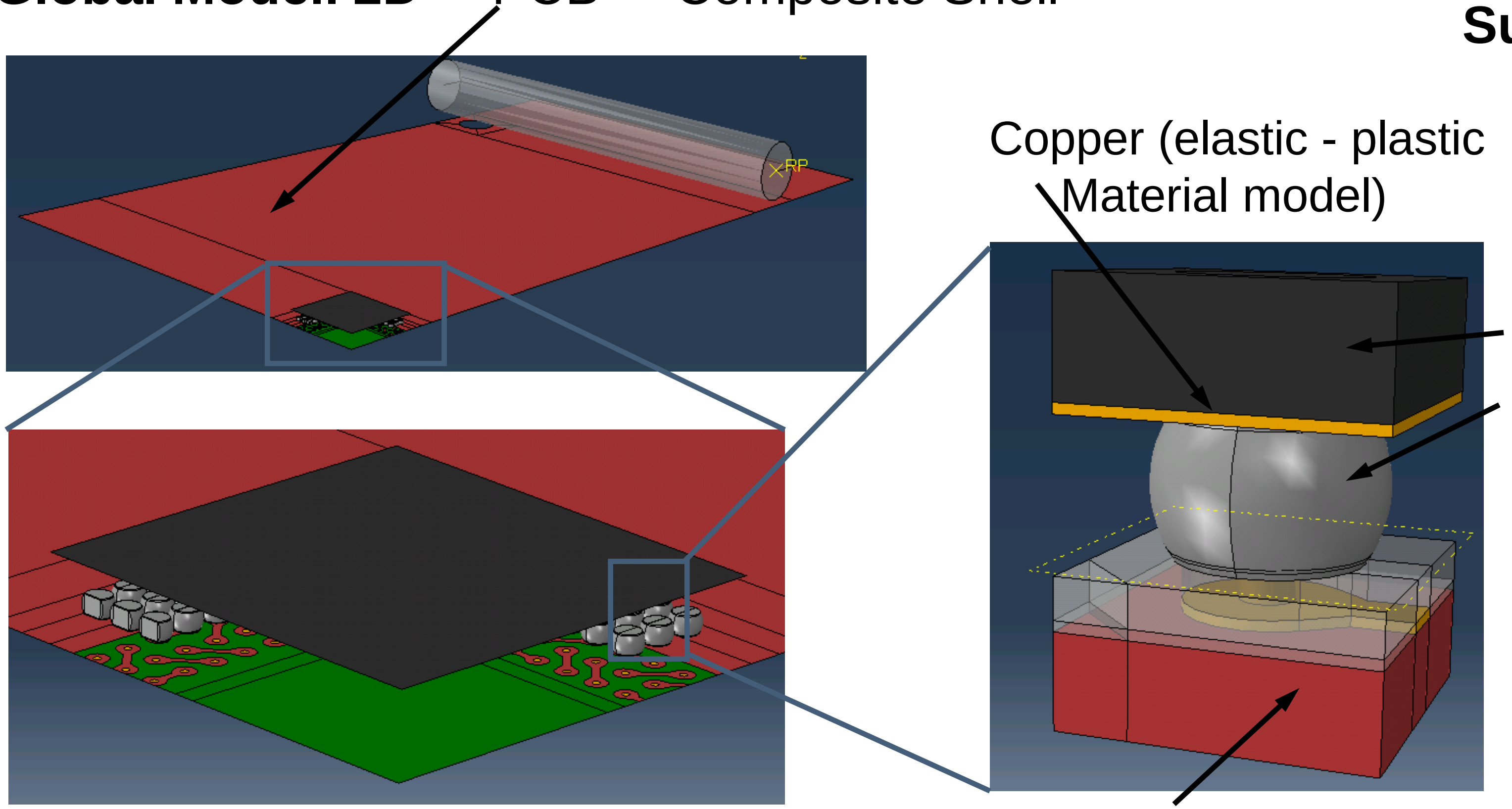
Material	Type	Glass type	Resin content %	E1 MPa	E2 MPa	E3 MPa
405335	A	106	75	7618	7729	
405651	A	1080	62	11693	10451	
405698	A	1501	46	16493	16037	

Simulation

Simulation Model - ABAQUS

Global Modell 2D PCB = Composite Shell

Sub-model 3D



Copper (elastic - plastic Material model)

Component+

Solder ball

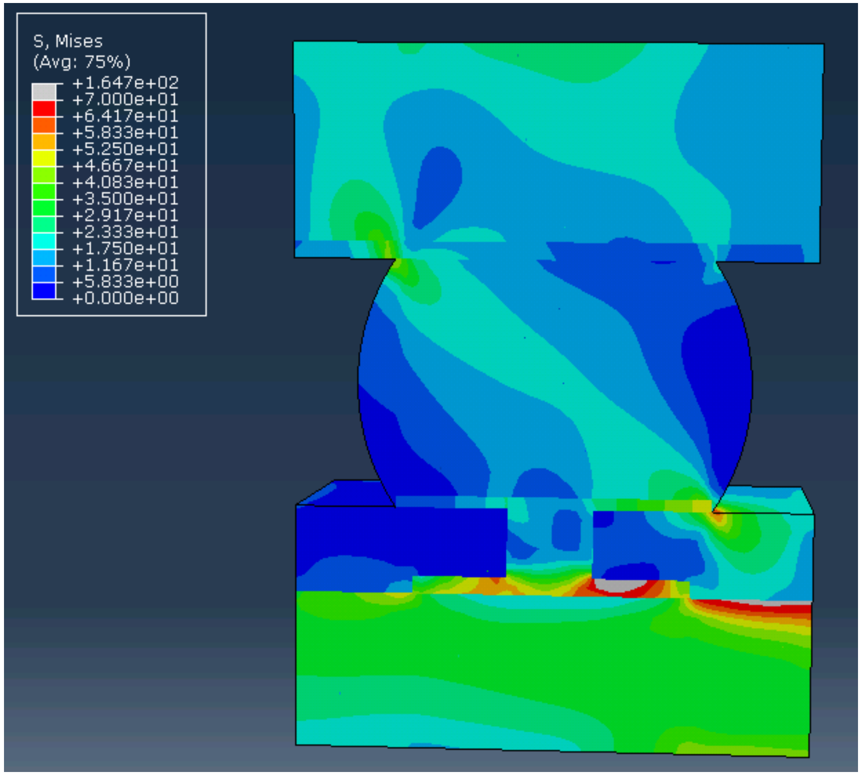
(Literature)

Elements: ~ 120 000
Time: ~ 1hr (8 CPUs)

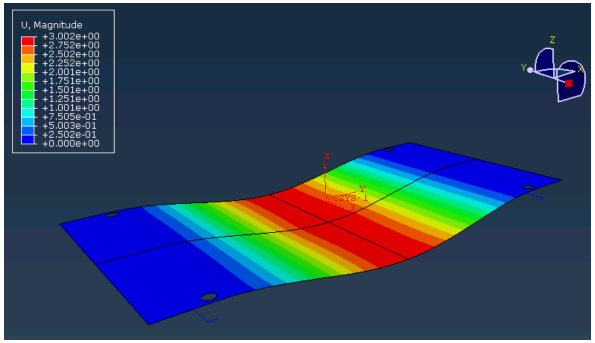
Prepreg (linear-elastic orthotropic Material Model)

Elements: ~ 200 000
Time: ~ 10 min (8 CPUs)

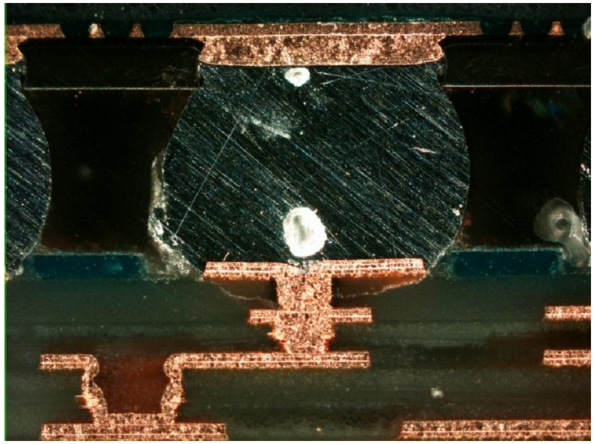
Simulation Sub Model



Mises Stress in a cross section of the Sub Model

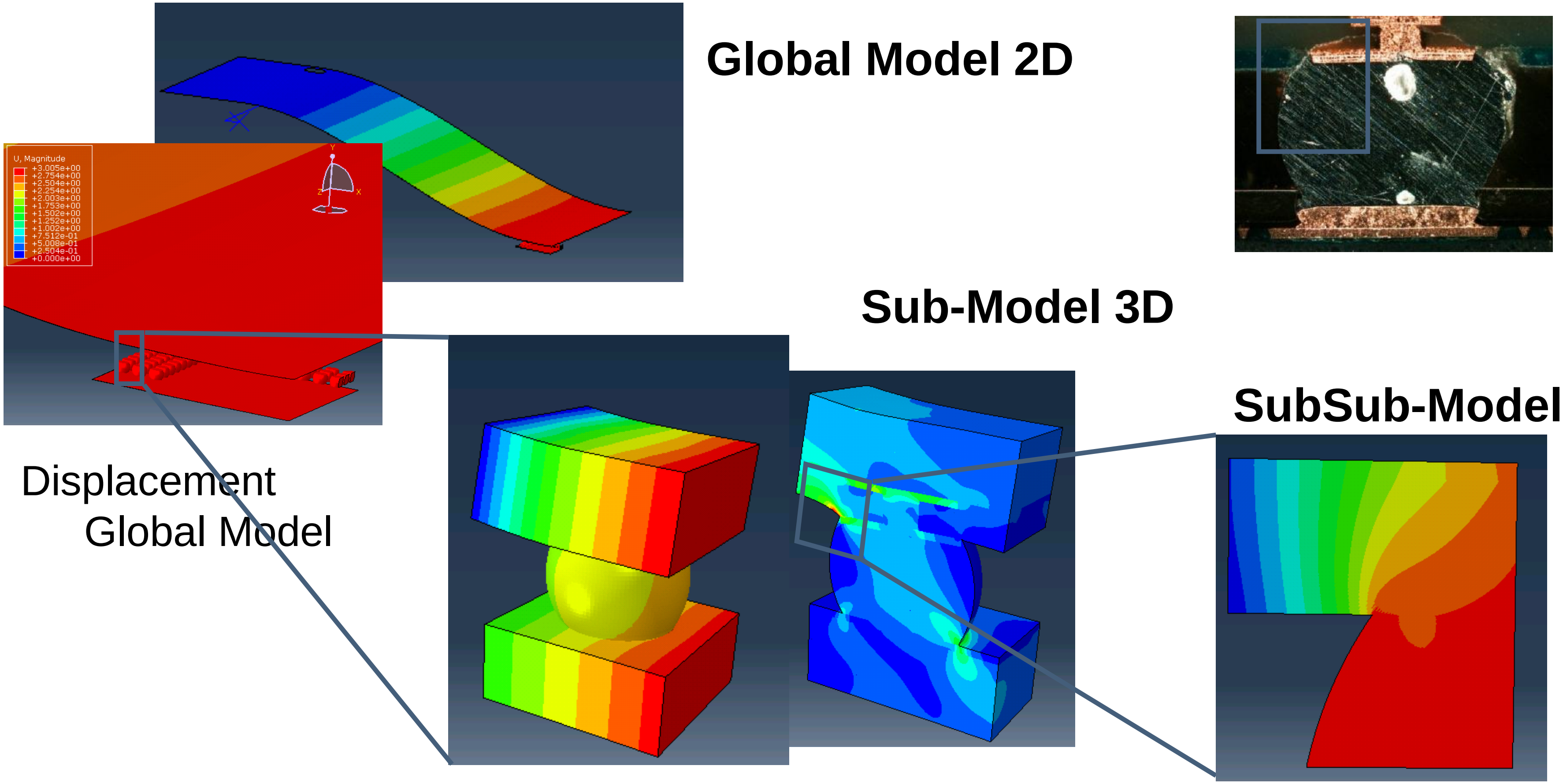


Deflection of the PCB under applied load



Typical Failure in a Board Level Cyclic Bend Test

Simulation SubSubModel



Global Model 2D

Sub-Model 3D

SubSub-Model 2D

Displacement
Global Model

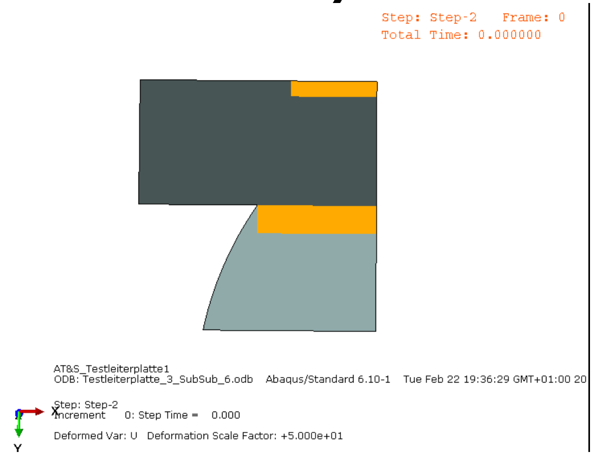
Displacement
Sub Model

Mises Stress
Sub Model

Displacement
SubSub Model

Damage Simulation

X FEM Simulation (Cohesive Zone Law Model)

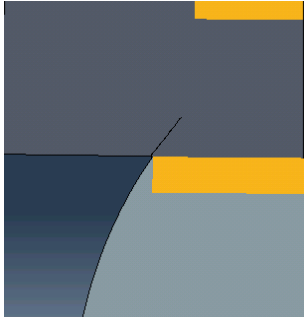


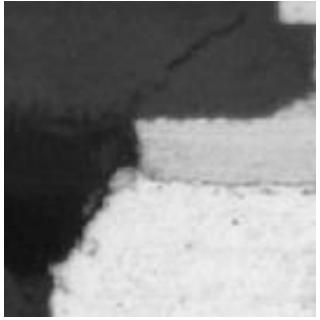
Step: Step-2 Frame: 0
Total Time: 0.000000

AT&S_Testleiterplatte1
ODB: Testleiterplatte_3_SubSub_6.odb Abaqus/Standard 6.10-1 Tue Feb 22 19:36:29 GMT+01:00 20

Step: Step-2
Increment 0: Step Time = 0.000
Deformed Var: U Deformation Scale Factor: +5.000e+01

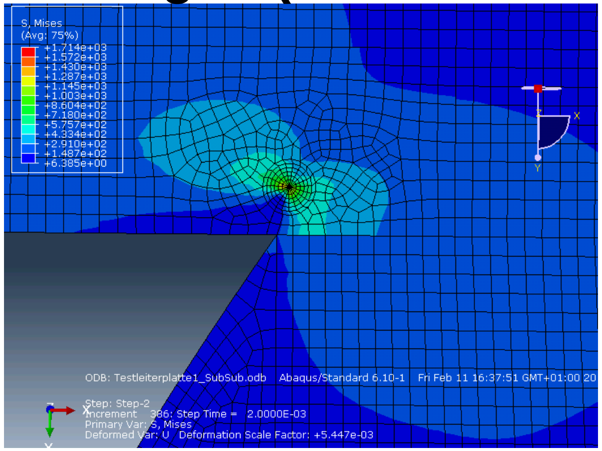
Crack start/-propagation





Elements: ~ 22 000
Time: ~ 12Std (8 CPUs)

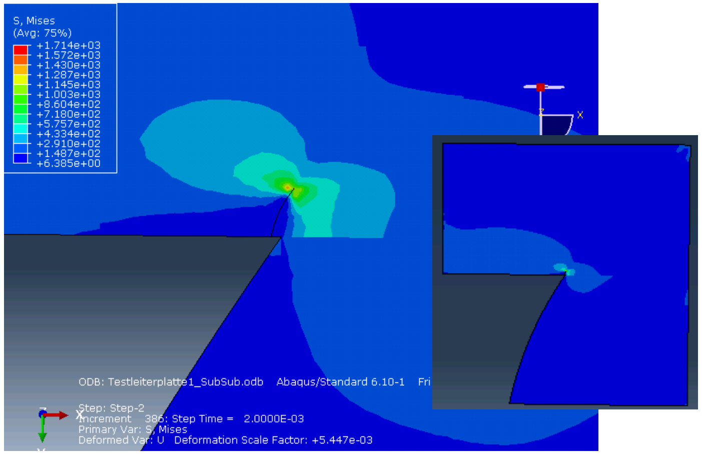
J-Integral (based on crack)



S, Mises
(Avg: 75%)
+1.714e+03
+1.572e+03
+1.430e+03
+1.287e+03
+1.145e+03
+1.003e+03
+8.604e+02
+7.180e+02
+5.757e+02
+4.334e+02
+2.910e+02
+1.487e+02
+6.385e+00

ODB: Testleiterplatte1_SubSub.odb Abaqus/Standard 6.10-1 Fri Feb 11 16:37:51 GMT+01:00 20

Step: Step-2
Increment 386: Step Time = 2.0000E-03
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +5.447e-03



S, Mises
(Avg: 75%)
+1.714e+03
+1.572e+03
+1.430e+03
+1.287e+03
+1.145e+03
+1.003e+03
+8.604e+02
+7.180e+02
+5.757e+02
+4.334e+02
+2.910e+02
+1.487e+02
+6.385e+00

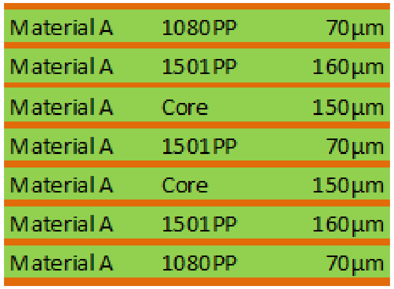
ODB: Testleiterplatte1_SubSub.odb Abaqus/Standard 6.10-1 Fri

Step: Step-2
Increment 386: Step Time = 2.0000E-03
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +5.447e-03

Elements: ~ 22 000
Time: ~ 1Std (8 CPUs)

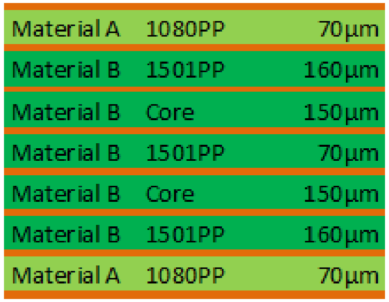
Damage Simulation

PCB1

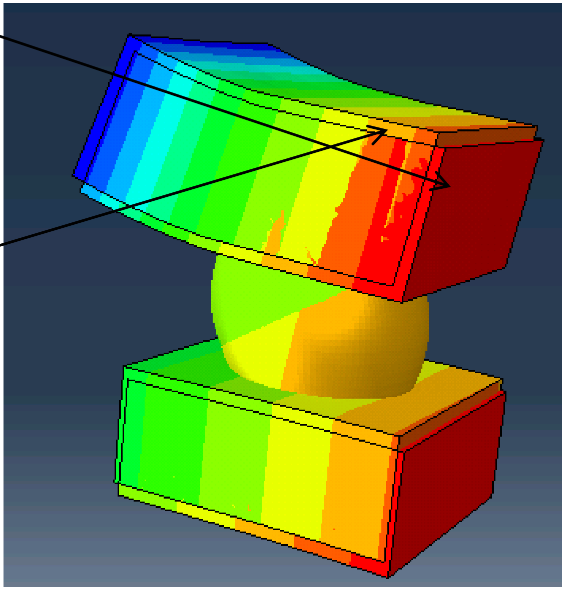


Material A	1080PP	70µm
Material A	1501PP	160µm
Material A	Core	150µm
Material A	1501PP	70µm
Material A	Core	150µm
Material A	1501PP	160µm
Material A	1080PP	70µm

PCB2

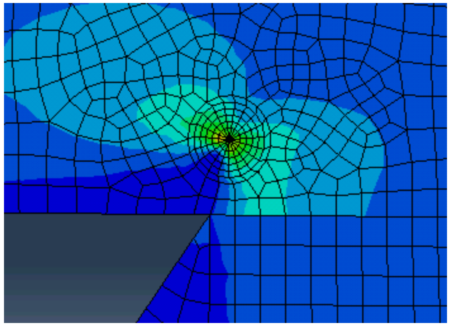


Material A	1080PP	70µm
Material B	1501PP	160µm
Material B	Core	150µm
Material B	1501PP	70µm
Material B	Core	150µm
Material B	1501PP	160µm
Material A	1080PP	70µm



Displacements

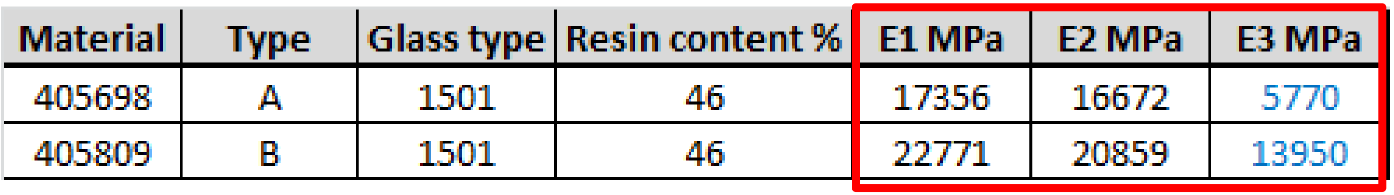
J-Value as Indicator



J-Integral PCB 1:
179 J/m^2

J-Integral PCB2:
209 J/m^2

Material Data



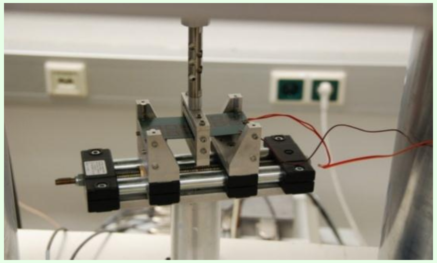
Material	Type	Glass type	Resin content %	E1 MPa	E2 MPa	E3 MPa
405698	A	1501	46	17356	16672	5770
405809	B	1501	46	22771	20859	13950

Lifetime Prediction

Analysis

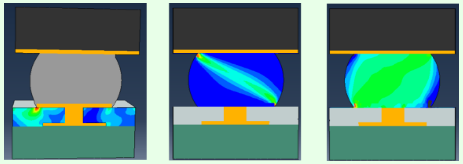
Carried out for one PCB type

Board Level Cyclic Bend Test



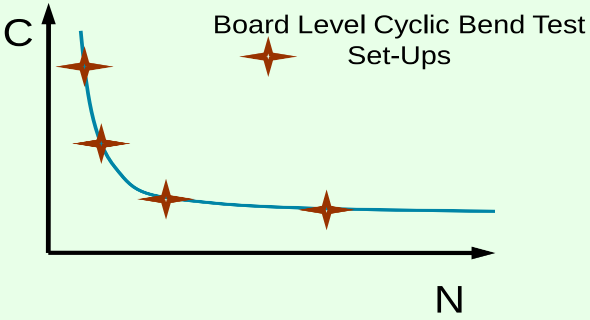
⇨ N

Submodel Simulation



⇨ C

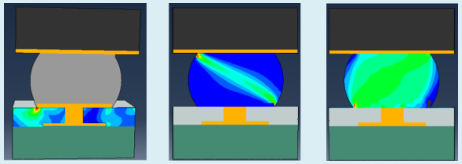
Characteristic Failure Curve



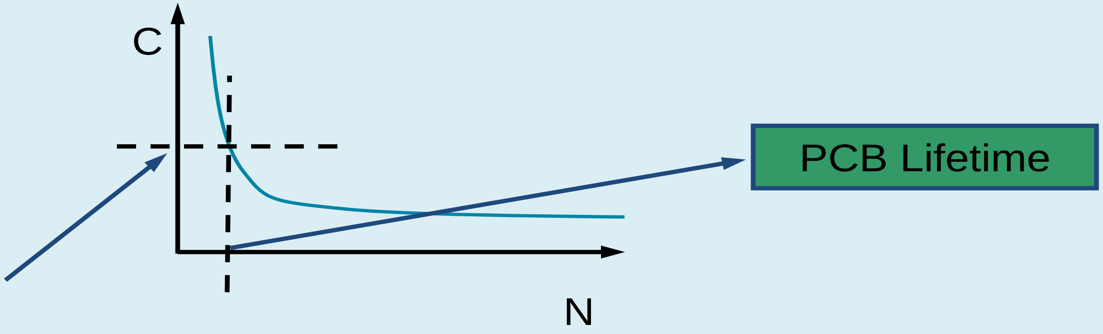
Prediction

Applied on unknown PCB types

Submodel Simulation



⇨ C



PCB Lifetime

N…Cycles to failure C…Local loading parameter

Results

- BLDT can be replaced by BLCBT
- In-Plane material data were determined experimentally
- Out-of-Plane data were simulated using micromechanics approach
- A Submodeling simulation model was applied for local loading situation
- A Fracture mechanics based model was used to determine J-Integral

Outlook

- The combination of both will allow generate failure curves
- Therefore a possible lifetime prediction methodology is suggested
- Further investigations may include different failure modes → Drop Test could be significantly reduced
- Methodology could be adopted for other reliability tests (e.g. TCT)