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Towards simulation of disassembly of bonded composite parts using the laser shock technique

P Kormpos, K Tserpes[1] and G Floros

Laboratory of Technology & Strength of Materials (LTSM), Department of Mechanical Engineering & Aeronautics, University of Patras, Patras 26504, Greece

[1]kitserpes@upatras.gr

Abstract. In this work, a model for simulating the laser shock-based disassembly of composite components is developed using the LS-DYNA explicit code. The laser shock technique has been used in the past for the non-destructive testing of adhesive bonds, but with appropriate adjustments it is possible to create a localized tensile stress that is high enough for adhesive failure to occur, making it suitable for use in the disassembly of bonded parts. In this first attempt, we focus on the development of a multiple loading instances simulation process, aiming to completely debond two carbon fiber reinforced plastic (CFRP) plates. The process of laser shock for disassembly requires an increased number of loading instances in order to cover the full bonded area. That, in addition to the short time duration in which the phenomena are evolved, poses a serious challenge for the numerical simulations, and thus a reliable procedure must be defined in terms of functionality and computational cost. Indeed, an iterative method, where the deformed model is used as input in subsequent simulations is evaluated, optimized and compared with a more traditional single model simulation.

1. Introduction

According to Airbus' PAMELA report 85% of the aircraft can be recovered, 70% can be recycled while 15% can be reused [1]. When an aircraft reaches its EoL, the decision that the owning company has to make is to resell or enter the disposal and recycle (D&R) process.

In the D&R process there are two options. Parts that can be removed are going to be reused, either maintaining their primary function, in which case it is required to be recertified, or they can be repurposed for an alternate use, meaning they need to be reworked or remanufactured. The other option is the recycling process. During that the materials of the aircraft are being sorted and separated. Materials that are well suited for recycle are entering a secondary recycling process, resulting in high quality virgin material. While materials that are not as well suited for recycling enter a downcycling process which results in virgin material of lower quality. Finally, materials that cannot be recycled are considered waste and end in landfilling [1]. Material separation and dismantling consists of various strategies, that are using a combination of disassembly and cutting (shredding, smart shredding, gross cutting, detail cutting, smart disassembly etc.) in order to achieve the best cost-benefit process for each type of aircraft [3]. Moving more towards disassembly strategies the cost increases significantly, but the process yields the best material segregation as well as the option to reuse some of the parts.

Current material separation strategies do not have a clear process for separating bonded structures, and adhesives typically lower the quality of the EoL products. Current research is focus on creating reversible adhesives [4]. While this is a great way to make future aircrafts more sustainable, aircrafts that reach their EoL now have been designed over 20 years ago and around 6600 aircrafts are expected to reach their EoL in the next decade [2]. For that reason, a new disassembly process for adhesively bonded structures is being developed, using a known technique called laser shock. This technique can potentially separate bonded structures without damaging the materials involved, leaving the option for reuse of the components. The development of the process requires simulations to guide the laser and the parameters so that the materials involved don't get harmed.

2. Laser shock introduction

Laser shock is the process of creating shockwaves inside the material using a high-power laser and it is based on laser/matter interaction phenomena and shock theory. To generate a laser induced shock wave a laser is focused on the surface of the material. Because of the high level of energy, the laser/matter interaction is resulting in a plasma expansion creating by reaction a shock wave in the material. The pressure that is created by the plasma expansion can be further increased using water confinement. The shock wave propagates inside the material according to its properties. When the shock front reaches the back face of the material it is reflected as a release wave bringing the pressure back to zero but accelerating particle velocity. At the same time another release wave is formed at the front face due to the unloading of the surface. The coincidence of the two release waves is resulting in high tensile stress[4].

This technique has been used in the past as a method of non-destructive testing of adhesively bonded structures [6], and recently as a method of selective paint stripping for aeronautical applications [7]. With appropriate calibrations it is possible to create high enough localized tensile stress to create a debonding on an adhesive joint in order to disassembly bonded structures.

3. Laser shock simulations using a multi-step process

In general laser shock technique must be calibrated by numerical simulations in order to understand the fast-evolving phenomena. The standard procedure is to use finite element analysis (FEA) for model creation, which then has to be validated by experimental data. Such simulations have been conducted in the past [4], but the focus was on a single loading instance. Disassembly simulations on the other hand, need multiple loading instances to achieve a full debonding of the involved parts. Such simulations can be quite challenging for the FEA codes and it is almost impossible to be conducted in a single simulation. For that reason, a multistep approach is being considered.

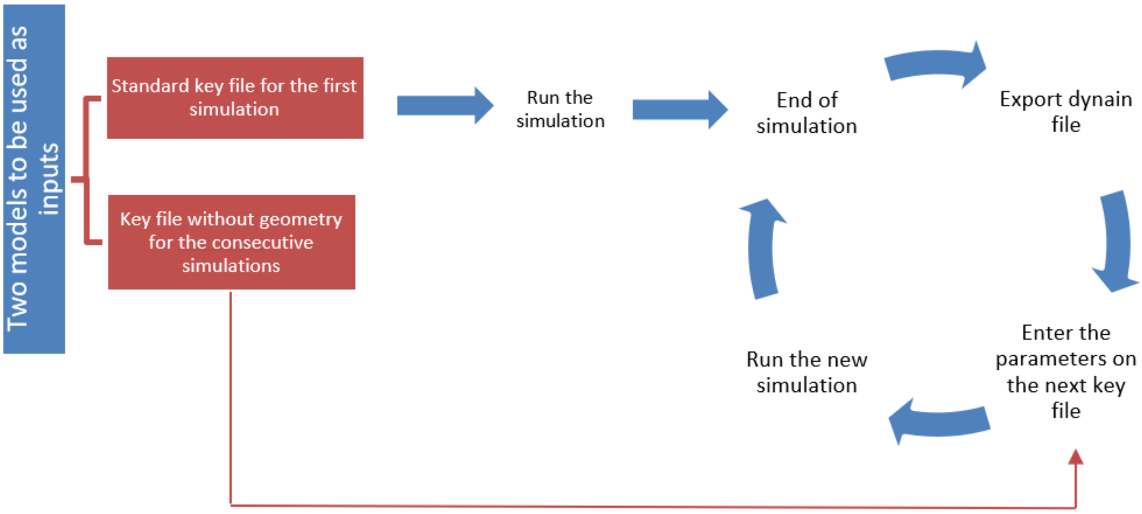

Figure 1. Multistep methodology in LS- DYNA

Using LS-DYNA explicit code it is possible to use the output of a simulation as a new input in a subsequent key file. To achieve this, two key files are needed. The first file is a standard key file containing the required geometry and parameters to conduct a simulation. The second file is a key file which contains no geometry (elements or nodes), and its purpose is to accept the output of a simulation in a form of a dynain file using the keyword *INCLUDE. Dynain files are LS-DYNA files that contain geometry, element history variables and initial stress and strains. This file is typically used in dynamic relaxation simulations to create an initial condition or preload. The main advantage of this file is that it can pass a deformed geometry to a second simulation, thus creating a multistep process.

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3.1. Material models

For a standard disassembly simulation there are at least 2 materials involved. The main parts and the cohesive bonding them. For the simulation of the main parts, it is mandatory to calculate the shockwave propagation and any damage that the shock is causing. For that reason, composite materials are being modelled using the LS-DYNA material MAT_162. It is a composite damage model which includes a delamination damage mode, this is mandatory as the main damage mode that is being caused by laser shock is delamination [9].

The joint is modelled using Cohesive Zone Method (CZM). In LS-DYNA this can be done by MAT_138, which is using a bilinear traction-separation law.

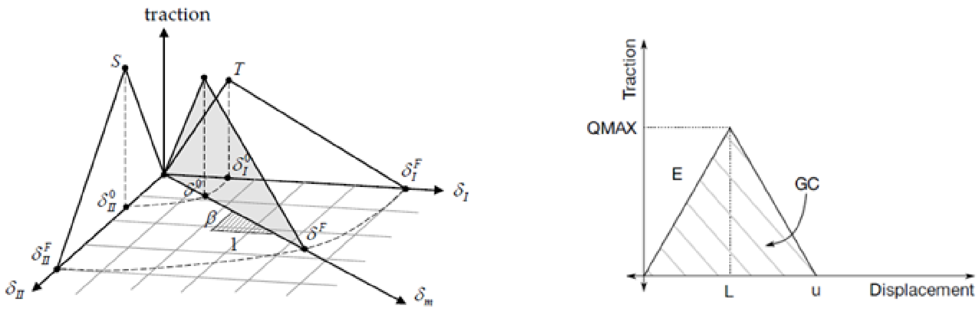


Figure 2. Bilinear Traction-Separation law [10]

4. Validation of the multi-step process

Although it seems possible to use a dynain file as a method of braking down a simulation to multiple steps, there is a certain degree of uncertainty involved, especially when complex material models are being used, as it is the case with laser shock simulations. Both CZM and material 162 are sensitive to their history variables to output the results. So, it needs to be verified that those materials are behaving as they should in a multi-step process. For this reason, a series of evaluating trials is being conducted before this method can be used in a disassembly simulation.

4.1. Mode I multi-step simulation for CZM evaluation

For the CZM evaluation trial a simple mode I simulation is being conducted. The goal is to observe the bilinear law in a series of subsequent simulations. For that a single cohesive element of a Double Cantilever Beam (DCB) model is being observed. First the element is being loaded until it enters the separation area, and it is considered damaged. But the element has not reached the maximum displacement, so it hasn't failed. After that the DCB is unloaded, a dynain file is exported to be used in the second simulation. The second simulation is loading again the DCB until the element fails. The expected behaviour is that the element is going to reach a maximum stress that it is the same as the stress at the time it got unloaded in the previous simulation. And then it is going to fail. Before this trial a reference model is needed so that the points of maximum stress and failure are clear.

Table 1. Reference model Results

Element ID: 1503	
Load	10 mm s^{-1}
Failure time	0.028 s
Max σ_z	8.18MPa
Time of max σ_z	0.002 s

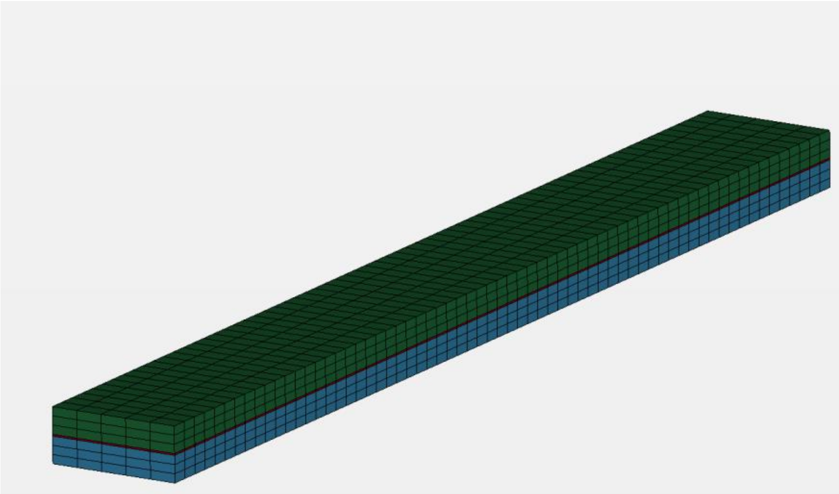


Figure 3. DCB model for Mode I simulation

From Table 1 we can extract the time at which the maximum stress is being observed, as well as the failure time. Between the two points in time the element is considered damaged, so a point in this range must be chosen for the two-step analysis.

As explained, on the second loading the max stress should be the same as the stress at the unloading time. From the results of tables 2 and 3 it is clear that the cohesive element works as it should and the history variables are maintained through the dynain file.

Table 2. First analysis results

Element ID: 1503	
Load	10 mm s-1, -10 mm s^{-1}
Max σ_z	8.18 MPa (@ t=0.002 s)
Unload time	0.013 s
σ_z at the unload time	5.2 MPa
Termination time	0.026 s

Table 3. Second analysis results

Element ID: 1503	
Load	10 mm s^{-1}
Failure time	0.28 s
Time of max σ_z	0.013 s
Max σ_z	5.19 MPa
Termination time	0.07 s

4.2. Cohesive evaluation by a laser shock model

The second trial that can validate the multi-step process, is a comparison of the damage pattern that occurs from a laser shock impact. The model that is used for that is consisting of two bonded carbon fiber reinforced polymer (CFRP) plates. Damage is only calculated at the CZM and not at the CFRP which is modelled using elastic orthotopic material model. The multi-step loading is consisting of two steps, each step contains a loading instance at a different spot. After the first loading instance is completed a dynain file is being exported to be used for the second loading instance. This methodology is then compared with a single simulation containing both loading instances, using time delay between the two.

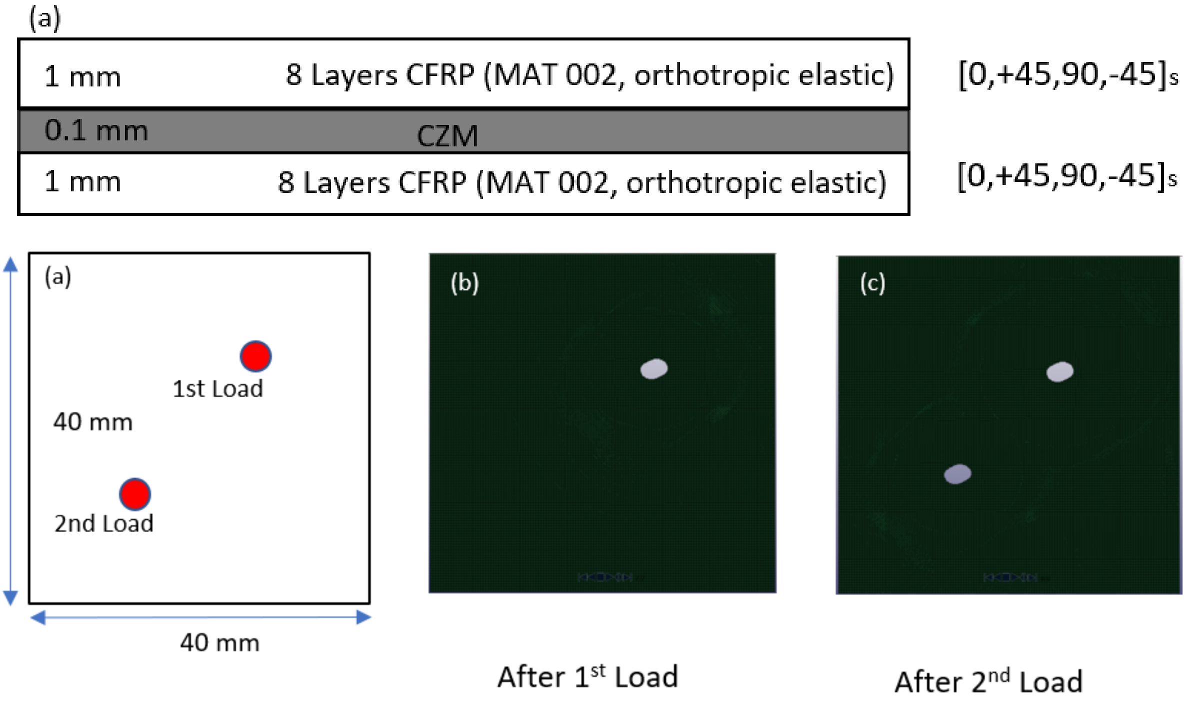


Figure 4. Model geometry (a), Damage pattern from multi-step Laser shock impact. After 1st load (b), 2nd load (c)

The goal of this comparison is to test if the results are deviating between the two methods. For the comparison to be correct, the time delay between the two loading instances is the same in both models.

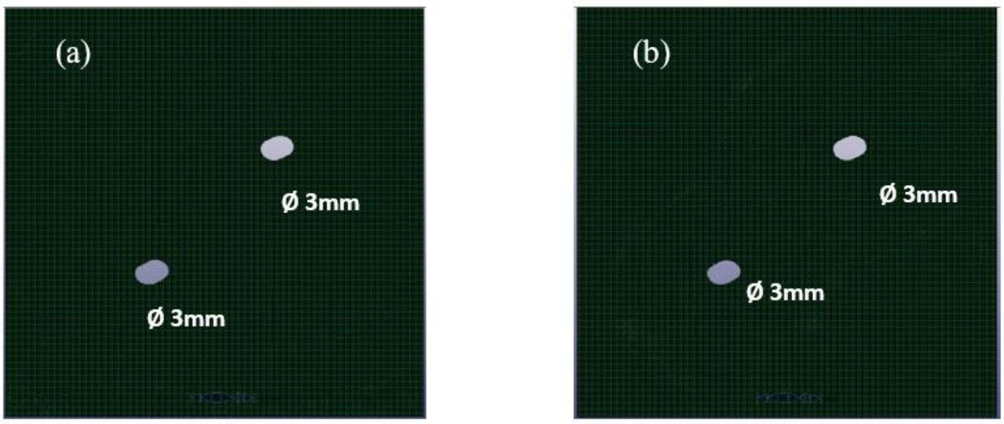
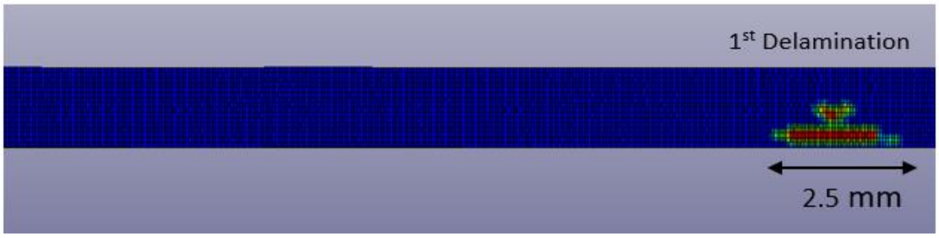


Figure 5. Damage pattern comparison, (a) Single simulation, (b) multi-step

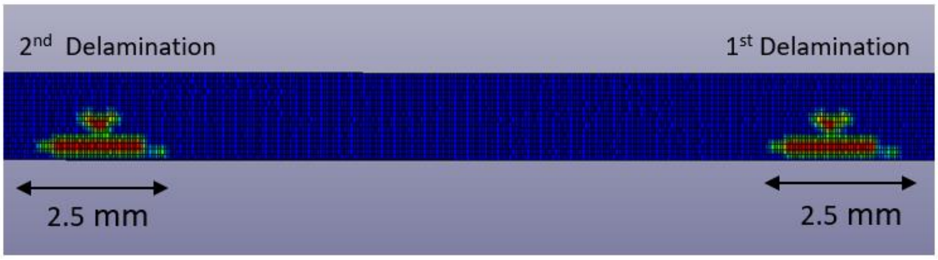
The damage pattern between the two seems to be identical, that means that the two-step analysis using the dynain can be used and correctly predict the damage occurring from laser shock impacts, on a CZM material model.

4.3. Composite damage evaluation using a laser shock model

Following the same evaluation methodology as before, this trial is going to validate the use of a multi-step process for the composite material model with damage prediction. For this trial a plate of unidirectional CFRP is being used and it is modeled using MAT_162. The procedure consists of a two-step loading simulation, the first load is going to be done in a single simulation and then the dynain file is being exported to be loaded a second time at a different spot. Then the same two loadings are going to be simulated in a single model using time delay between them.

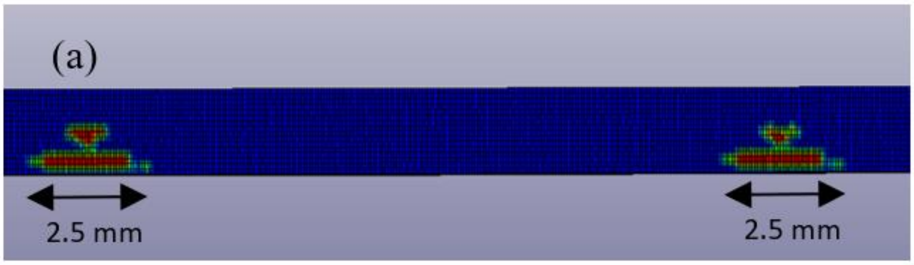


(a)



(b)

Figure 6. Damage pattern from two-step laser shock loadings, after first load (a), after 2nd load (b)



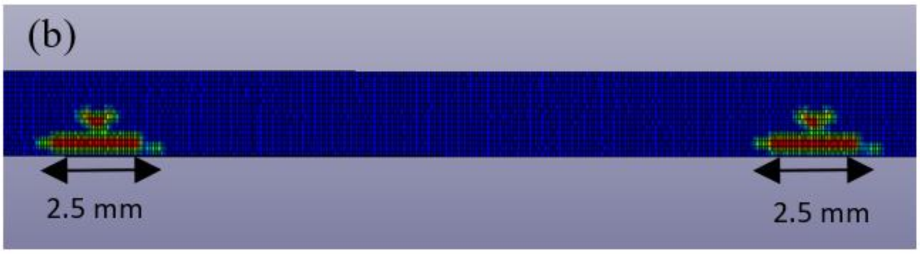


Figure 7. Damage pattern comparison, (a) single model, (b) multi-step model

It is clear that the damage pattern from the two methods is the same. This means that the multi-step method does not change the outcome of the damage pattern in material 162, which means that the method can be used for the simulations.

5. Disassembly simulation

After validating the multi-step methodology, it is used to simulate the disassembly process. The model that is used is a plate of bonded CFRP and the goal is to create a debonding with minimum to no damage at the CFRP. For such a debonding to occur, the plate cannot be hit by an extremely high energy, as it would be destructive to the material. Instead, the pressure that is being applied is set to 841 MPa, which aims to create damage at the bonded area without creating a debonding, after that a dynain file is being exported and then getting hit again with the same pressure to create the debonding.

1.75 mm	14 Layers UD CFRP (MAT162, composite damage)
0.1 mm	CZM
0.25 mm	2 Layers UD CFRP (MAT162, composite damage)

Figure 8. Geometry for disassembly simulation.

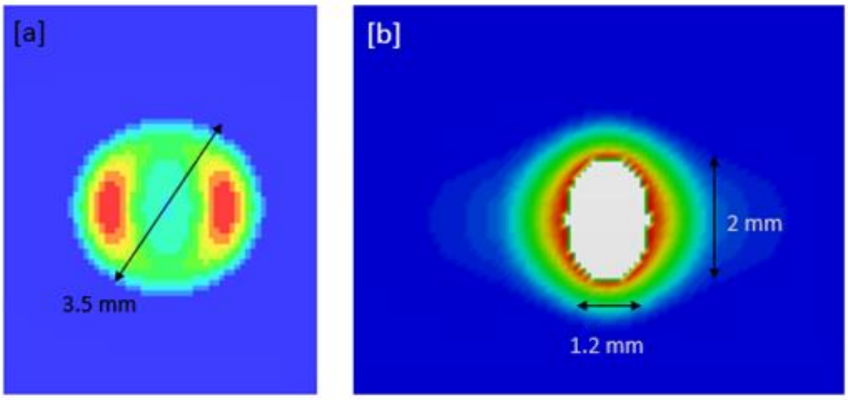


Figure 9. CZM at the loading spot, after the 1st load [a], after the 2nd load [b].

Indeed, after the first loading the CFRP is not damaged at all and the CZM is damaged at the loading spot in a circular pattern with diameter 3.5 mm. On the second loading the debonding is occurring and its dimensions are 2 mm x 1.2 mm and the shape of the debonding is explained by the orthotropic nature of the unidirectional composite, the damaged area after the second loading remains 3.5 mm. The second loading has created delaminations on the layers above and bellow the CZM.

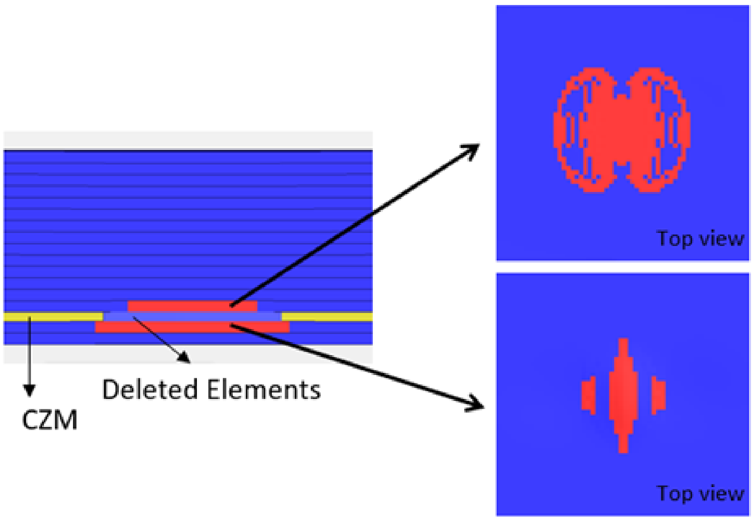


Figure 10. Delaminations caused by laser shock.

6. Conclusions

From the evaluation trials conducted to the multi-step simulation methodology, it seems that the process works as it should. History variables are conserved through the dynain file and the results are the same as a traditional single simulation, using time delay between the loads. This methodology is well suited for a disassembly simulation, or any kind of simulation that requires extra steps on a deformed model. The main problem of the method for now is that it is not completely automated, as for each model human interaction is required, mainly for the set up. Also, it is possible to simulate the disassembly process, this process seems promising, according to the simulations, it can cause localized debonding and although for now it seems to cause damage to the materials involved, with proper calibration it may be possible to eliminate the damage. Experimental data are needed for model validation and parameter calibrations.

7. Acknowledgment

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