Progressive Ply Failure Analysis

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Introduction

- What is Progressive Ply Failure?
  - The failure of a laminated composite in stages
  - The most highly stressed ply fails, followed by other plies as determined by the loading

Introduction

- Why is this important?
  - Many laminated composites can carry significant load even after the failure of the first ply
  - First Ply Failure (FPF) does not consider this additional load carrying capacity
  - Failure absorbs energy similar to plasticity in metals

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Benefits

- What is the real benefit?
  - Setting factors of safety in designs requires a knowledge of when failure really occurs
    - If failure occurs quickly, a larger factor is justified
      - Too low and an oddball load will result in failure!
    - If failure occurs slowly, a smaller factor may be appropriate
      - Too large and you are over-designing!

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Benefits

- Knowledge of the failure progression can help with design in other areas of the structure
  - Will a local failure spread and become catastrophic?
  - Can other parts of the structure take up the slack?
    - Can I design them to do so?
  - Can I modify my design to forestall initial local failures?
  - Can I modify my overall design to correct an over design or under design?

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Analysis

- So what do I get if I analyze it?
  - You answer a number of potentially important questions:
    - Is the failure of the first ply associated with abrupt failure of the component?
    - Is the stress re-distributed over adjacent plies maintaining the load-carrying capability of the part?
    - Is load re-distributed over adjacent elements?
    - How far is First Ply Failure from Last-Ply-Failure?
    - What is the evolution of the part from FPF to LPF failure?

Analysis

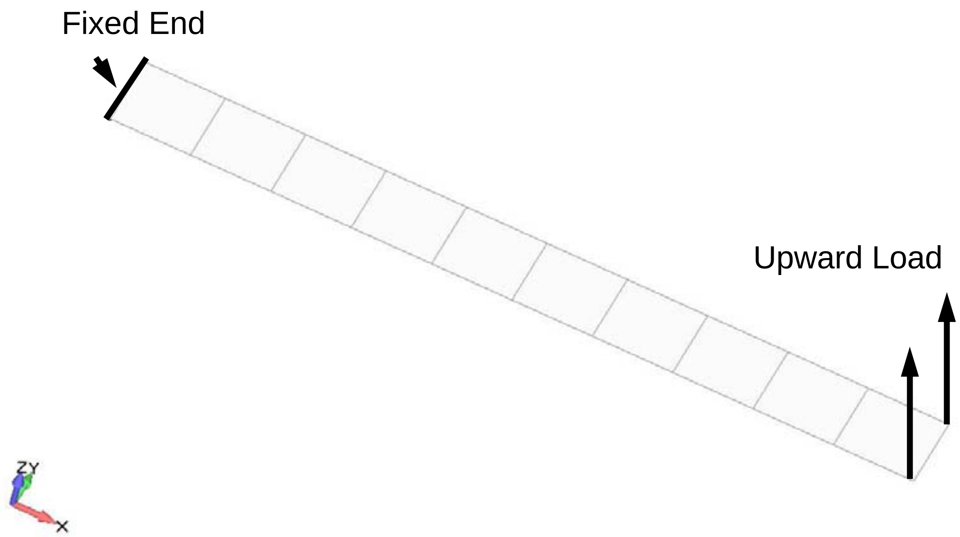
- Let's look at how progressive failure can be analyzed.
  - Most FEM codes use some form of Classical Lamination Theory (CLT)
  - Converts a layered composite to an equivalent homogeneous plate
    - Mass and Stiffness equivalent
    - No additional DOF
    - Ply results derived from element strains and curvatures

Analysis

- Progressive Failure can be incorporated into this formula by recalculating the equivalent properties once a ply fails
  - Requires a nonlinear analysis
    - Stiffness matrix changes
  - Failures can be updated
    - at the end of each increment
      - Simple to implement, minimizes run time
    - or as they occur
      - Can produce iteration issues if many plies fail almost simultaneously
  - Update will be a ‘failed’ stiffness for the failed ply
    - Intact plies unchanged

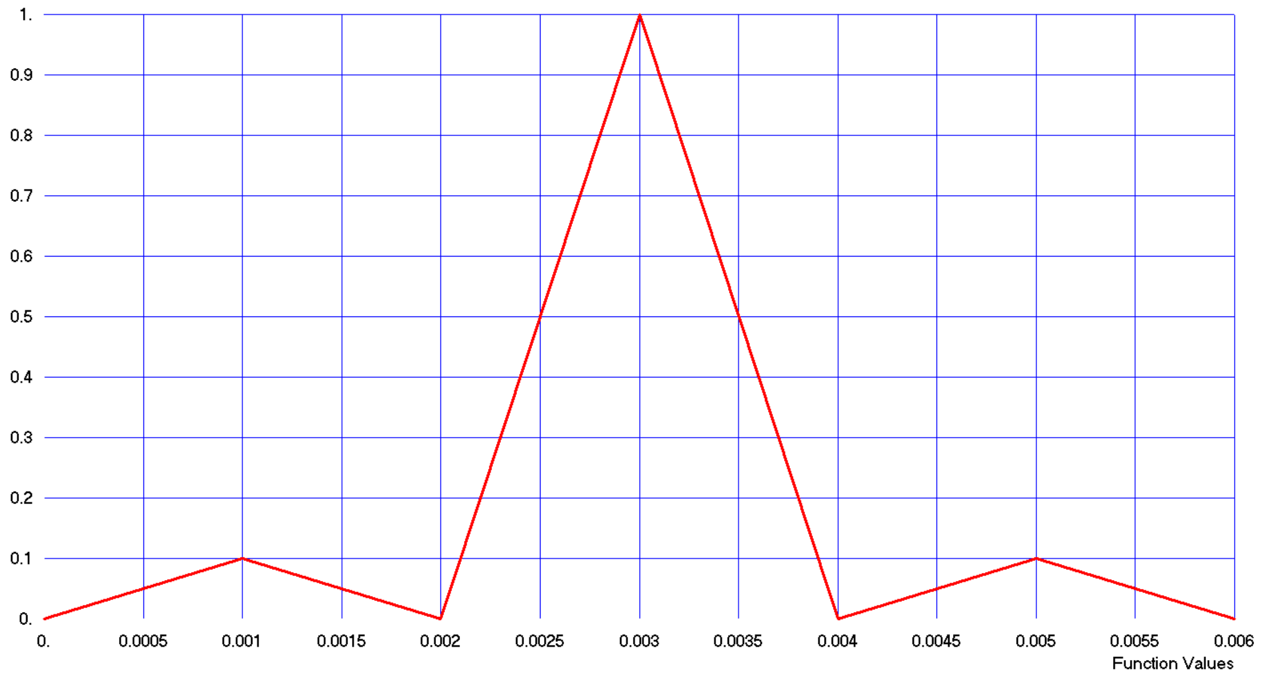
An Example…

- Here is a very simple model to illustrate a progressive failure analysis



An Example.

- This model will be loaded with three loading cycles over time, as such:



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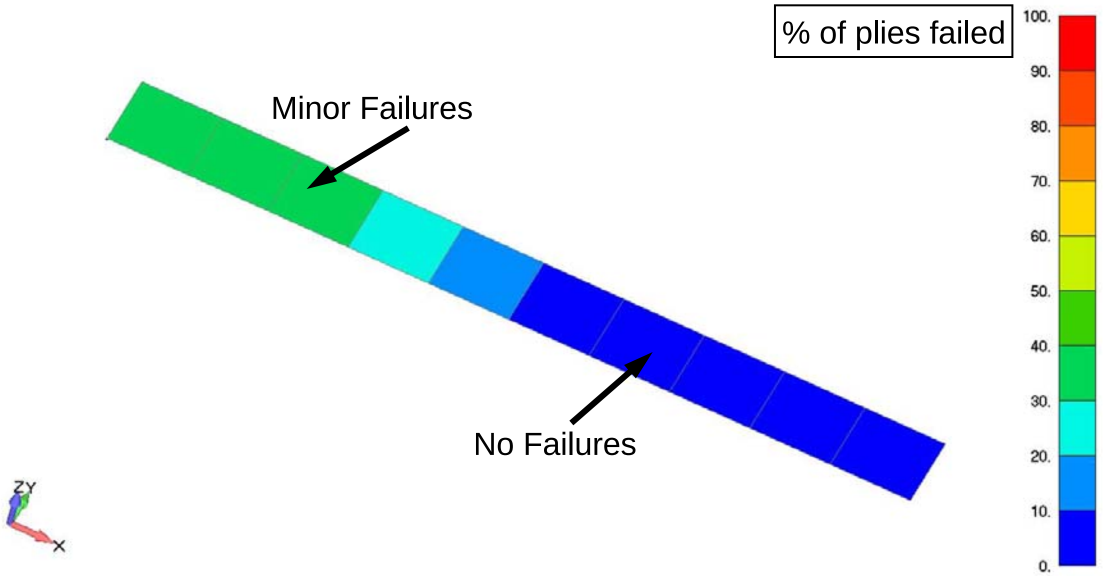
An Example

- On the first cycle, a few plies will fail, degrading the stiffness slightly.
- On the second cycle, many plies will fail
- The third cycle is a repeat of the first, but with a significantly compromised stiffness.

An Example

- After the first cycle, the damage is minimal



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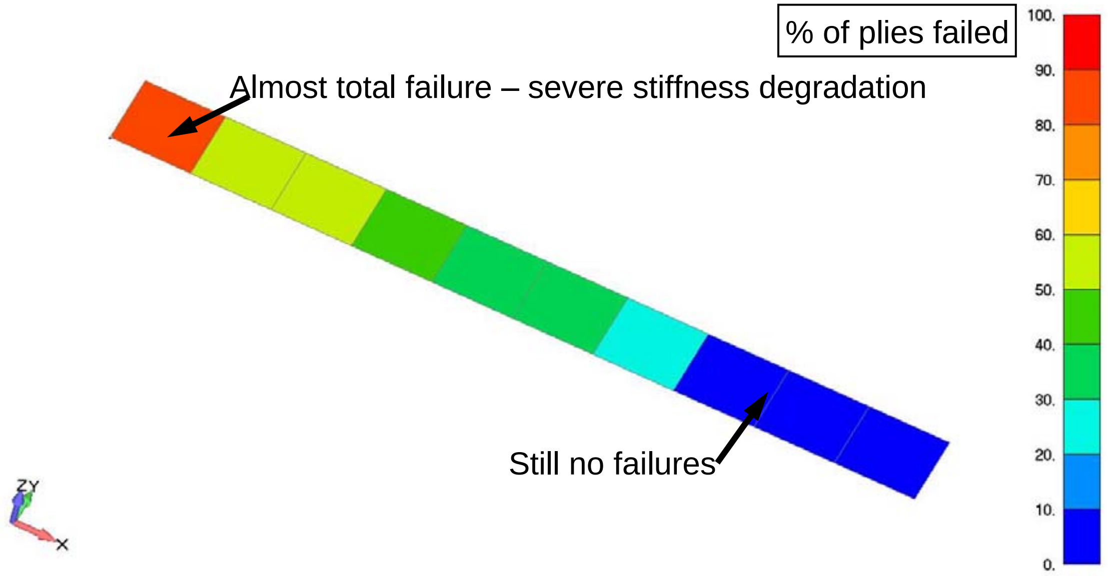
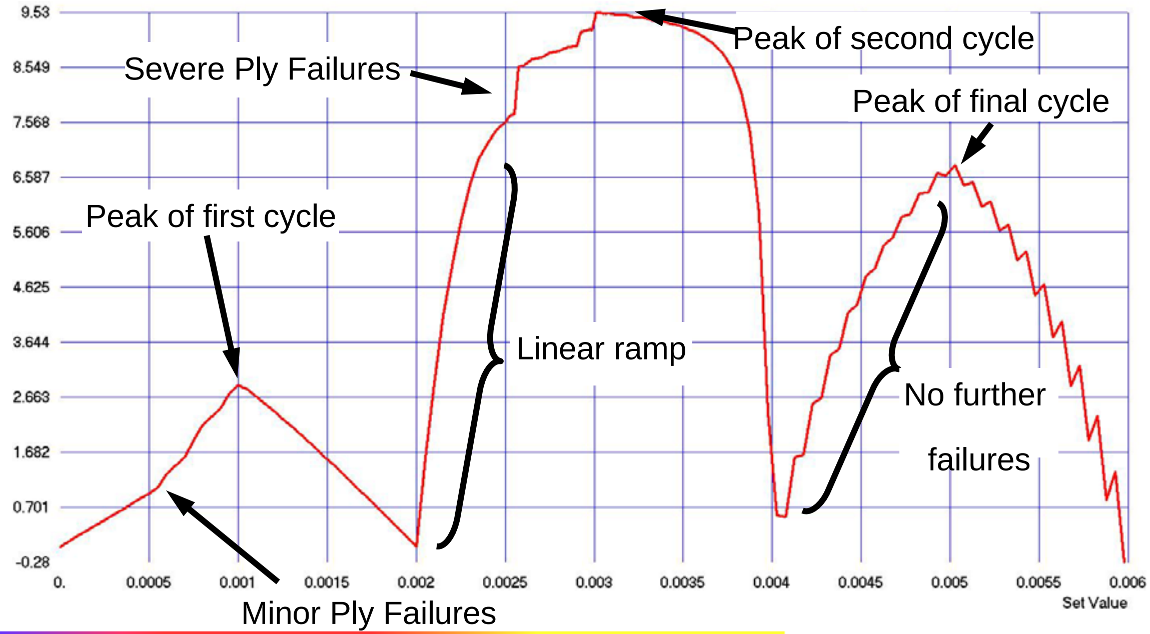
An Example

- After the second cycled, damage is extensive.



An Example

- The third cycle adds no damage, but the deflection is much greater than the first due to the reduced stiffness



An Example

- This example shows the cumulative effect of damage
- The larger deflection in the third cycle is a result of reduced stiffness because of damaged the laminate

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Analysis

- Lets revisit the questions asked earlier…

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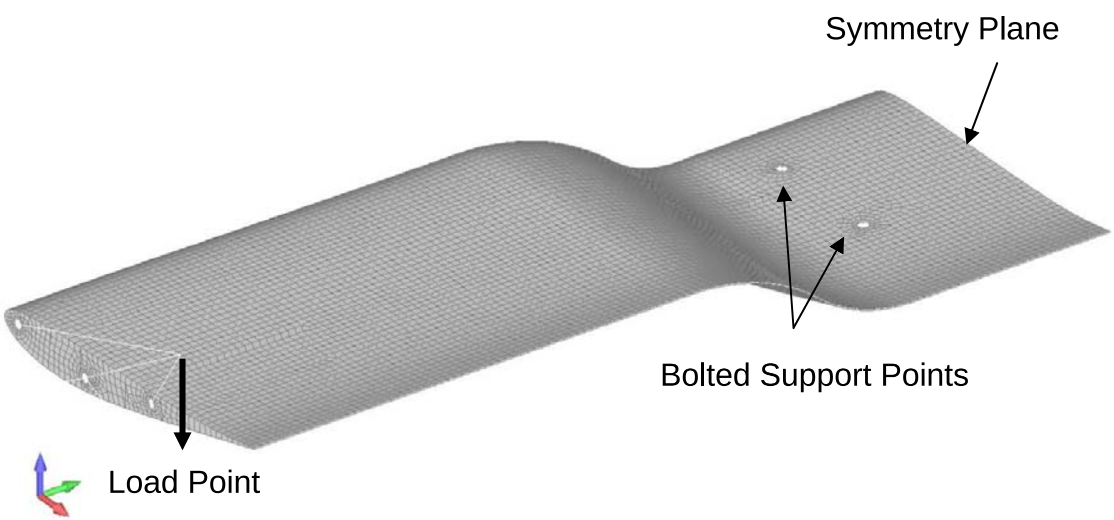
Analysis

- Is the failure of the first ply associated with abrupt failure of the component?
  - In some cases, the load may be such that the residual load carrying capacity of a part is insufficient to maintain integrity with a damaged laminate. In that case, a progressive ply failure analysis will show a swift failure of all remaining plies once the first ply has failed. This is useful information for determining margins of safety to incorporate into a design.

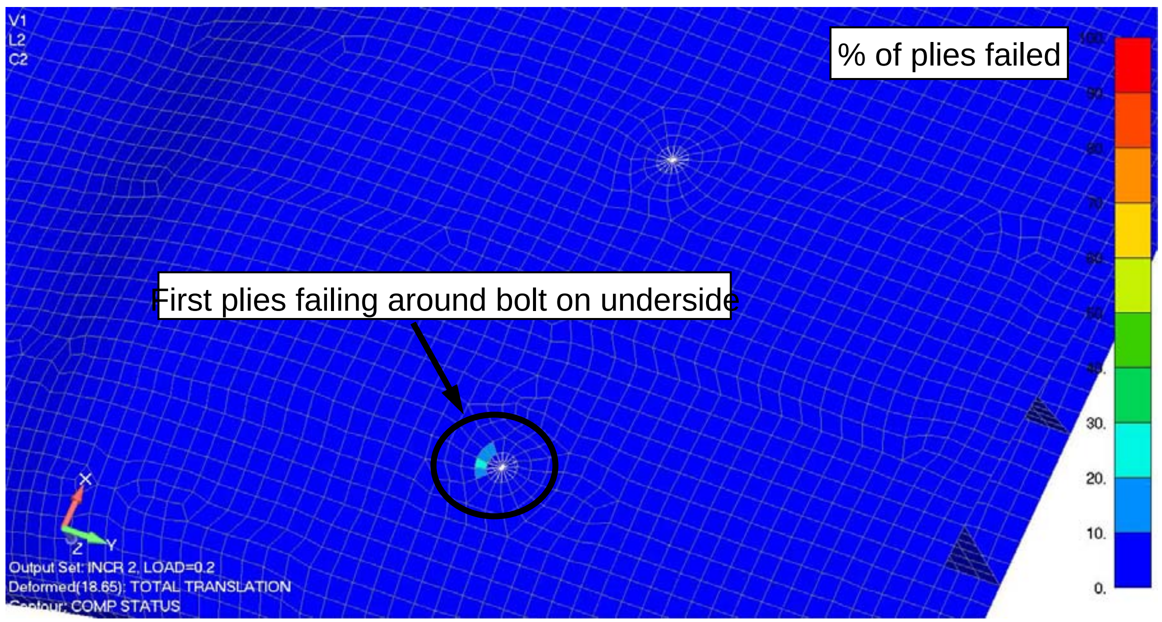
Swift Failure?

- Consider this model



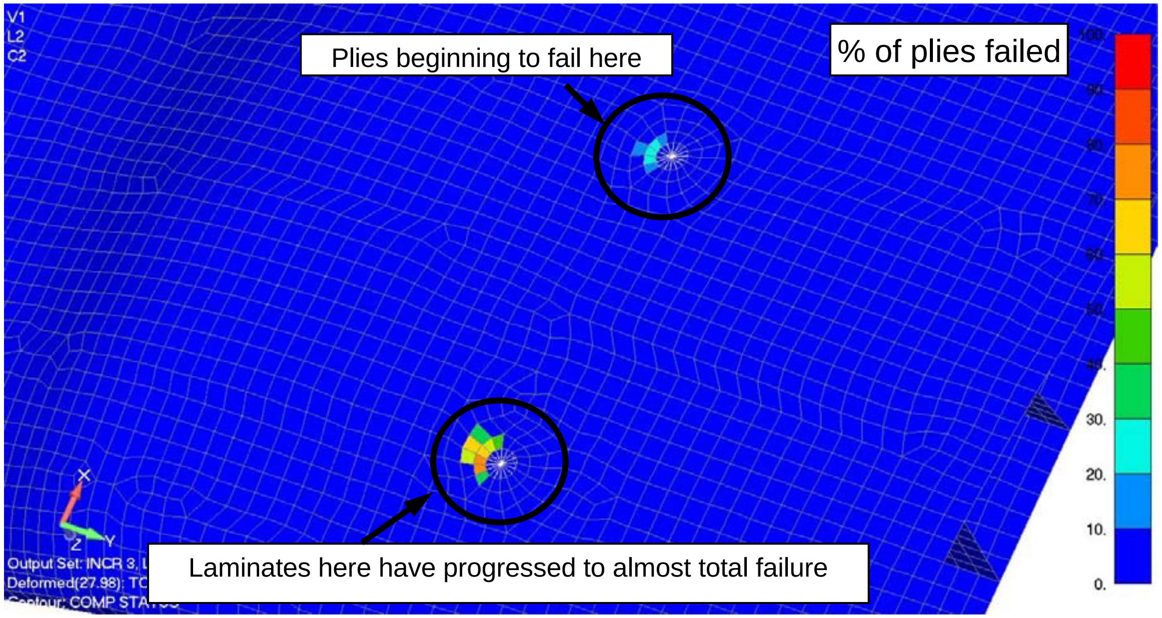
Swift Failure?

- On the first loading increment failure is noted around the bolted support points



Swift Failure

- On the second loading increment, those plies have progressed to almost total failure!



Swift Failure!

- Because of the concentrated loading, this model has little reserve capacity
  - Once failure starts, it progresses to total failure quickly.
  - A sufficient factor of safety should be used, as there is little margin for error.

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Redistribution to plies

- Is the stress re-distributed over adjacent plies maintaining the load-carrying capability of the part?
  - In some cases, failure of a single ply will simply result in the load being taken by other plies in the laminate. In this case, a progressive ply failure analysis will show that equilibrium is reached after failure of some plies, but that part does not fail catastrophically. Like the abrupt failure case, this information can assist in determining design margins.

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Redistribute to other parts?

- Is load re-distributed over adjacent elements?
  - It is possible that the partial failure of a section will redistribute the load to other parts of the structure. A progressive failure analysis would show where the loads end up, and can provide valuable insight into the design of the other members in order for them to take the additional load properly. An option may exist to channel the redistributed load away from critical members into ones designed for the additional load.

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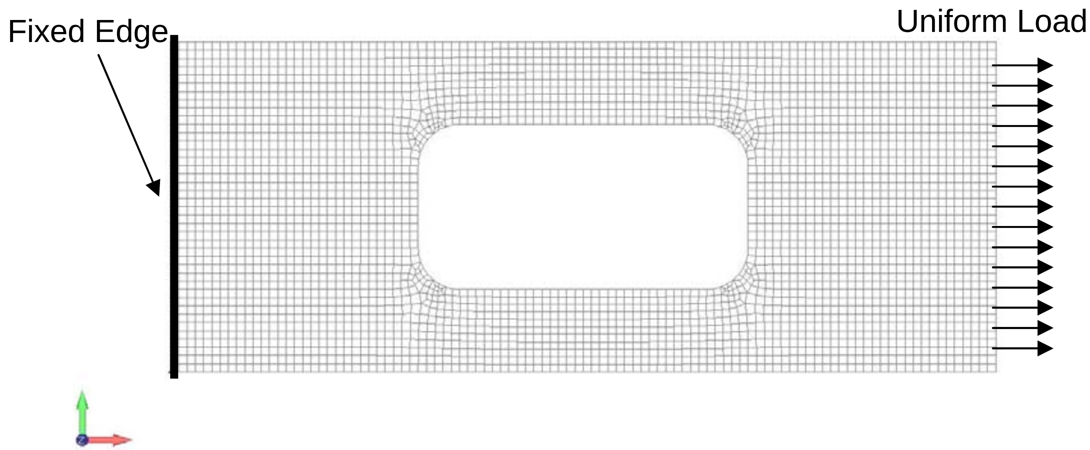
Reserve Capacity?

- How far is First Ply Failure from Last-Ply-Failure?
  - If the last ply fails relatively quickly after the first ply, it may make sense to use a FPF based design approach for the rest of the model, or for the rest of the design cycle. However, this would be hard to verify without at least one progressive failure analysis.

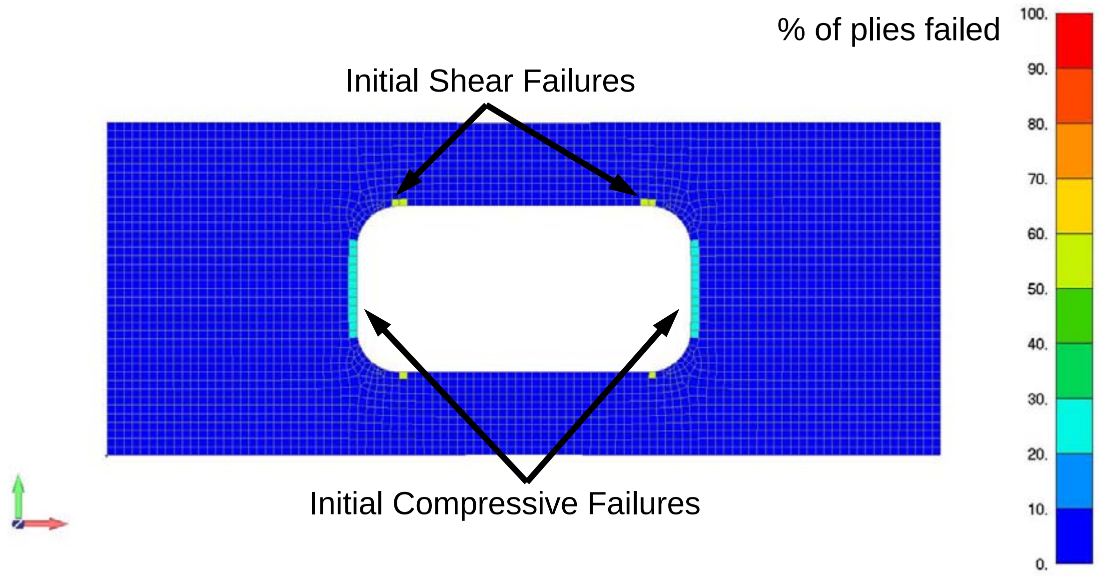
Reserve Capacity?

- Consider this model:



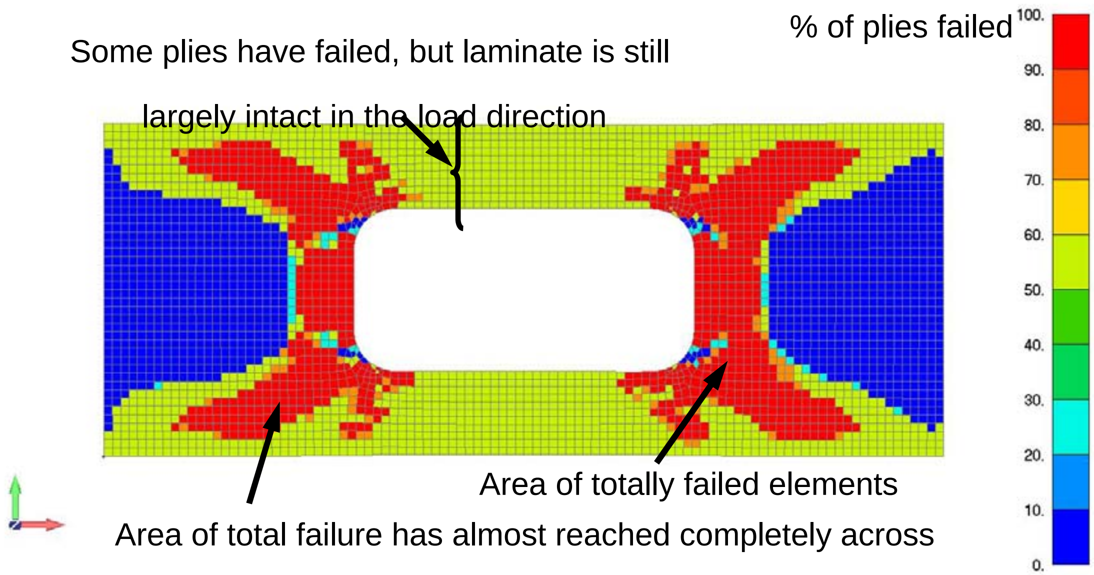
Reserve Capacity?

- Plies begin to fail very early in the loading cycle (10% of applied load)



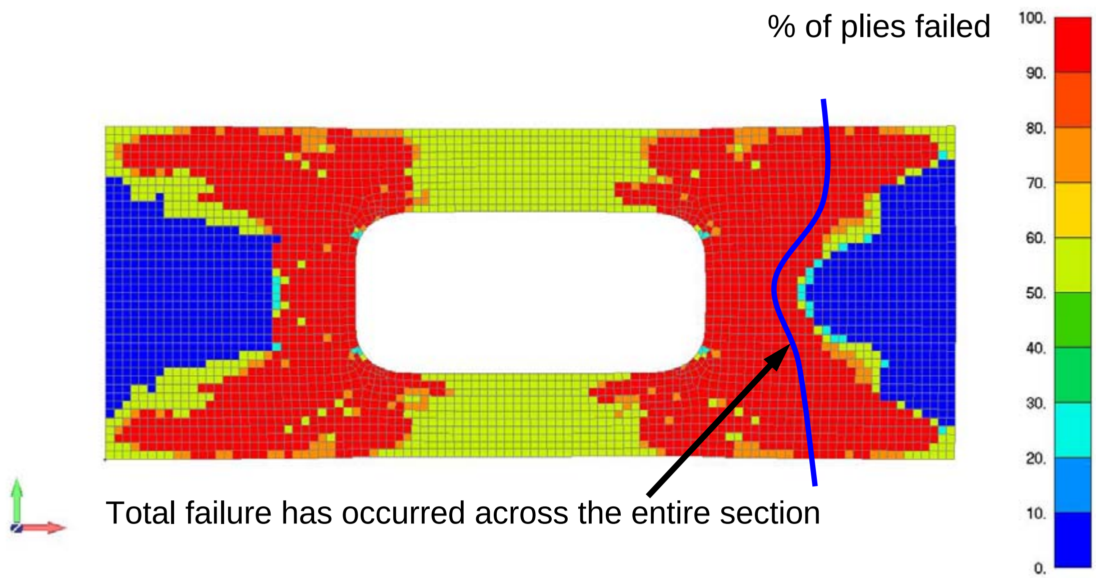
Reserve Capacity

- Plies and elements continue to fail gradually up to 55% of applied load



Reserve Capacity?

- The part finally lets go at 65% of applied load



Reserve Capacity.

- The initial (first ply) failures are in the elements around the hole and show up in the fourth load increment, corresponding to a load of ~4000 (Figure 6).
  - Closer examination of the failed portions shows that the elements at the end are placed in slight compression.
    - Because the compressive strength of this material is very low (compared to their tensile strength), even a slight compressive load causes failure.
  - The elements along the side of the hole are failing in shear, as the shear strength of this material is also very low.
- The load carrying capacity of the plate, which is provided almost entirely by tensile loading of the fibers, is practically unchanged.

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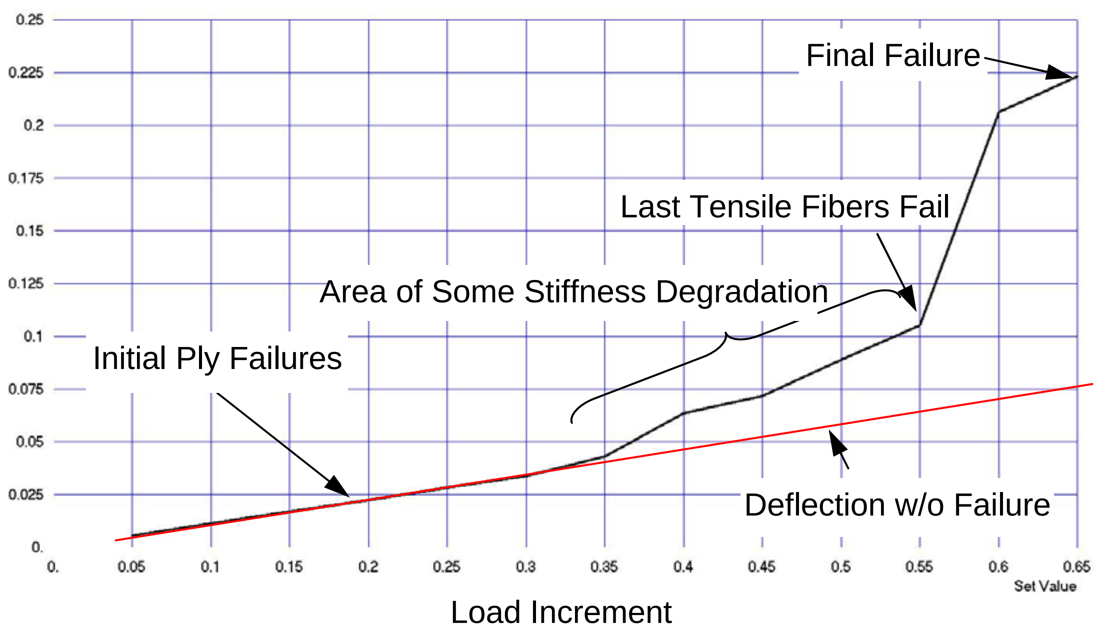
Reserve Capacity!

- If this plate were subject to a first-ply failure analysis, the load carrying capacity of the plate would be listed at <4000.
  - The stiffness of the plate is relatively unaffected up to a load of almost 11000 (Figure 7).
    - At that point, the fibers aligned with the load begin to fail and the stiffness begins to degrade.
    - But it isn’t until a load of about 13000 (Figure 8) at which point the last of the fibers aligned with the load fail in tension.

Reserve Capacity!

- This graph illustrates the end deflection of the plate as the load is increased.

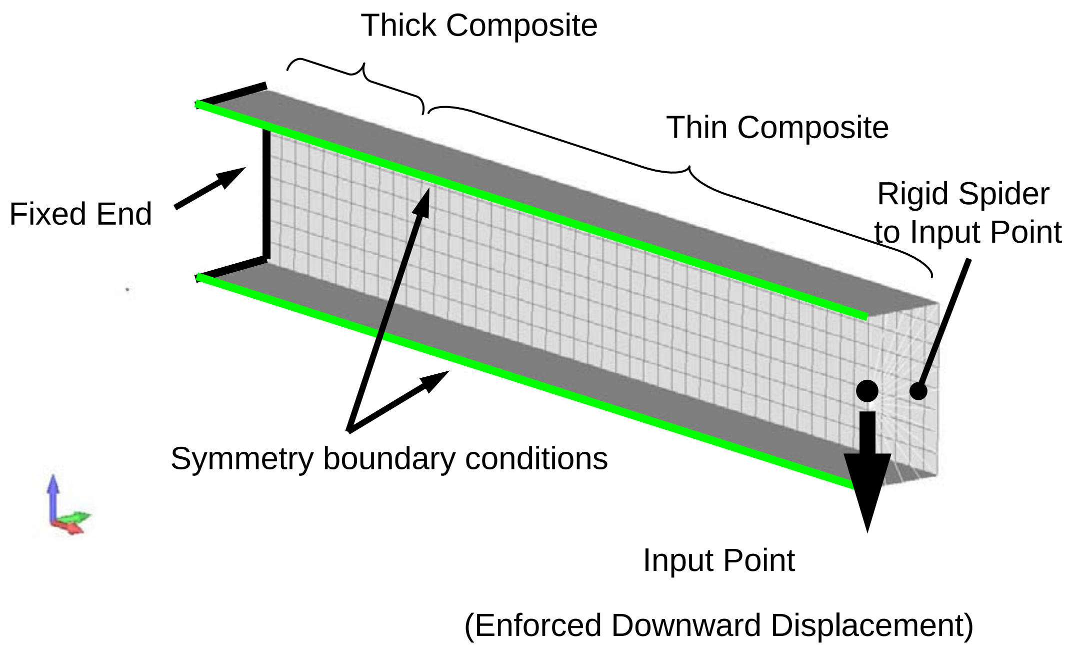


Evolution of Damage?

- What is the evolution of the part from FPF to LPF failure?
  - Because of the nonlinear nature of a progressive failure analysis, it should be noted that the progression from first ply failure to last ply failure is not necessarily a straight line.
    - It may be that a few plies fail initially, but that the remaining plies remain intact for a large portion of the loading cycle, only failing catastrophically at the very limit of the load.
      - This information maybe able to provide the basis for a redesign that eliminates the early failure, thus extending the range of the intact laminate considerably.
    - If most of the plies fail immediately, and the last ply only fails at the very end, it implies that the initial damage takes away most of the load carrying capacity of the laminate.
      - In this case, a FPF based approach would also work reasonably well.
    - Where and how do loads redistribute?
      - To other parts?
      - To other plies?
      - Different failure mechanisms?

Evolution of Damage?

- Consider this box beam model…



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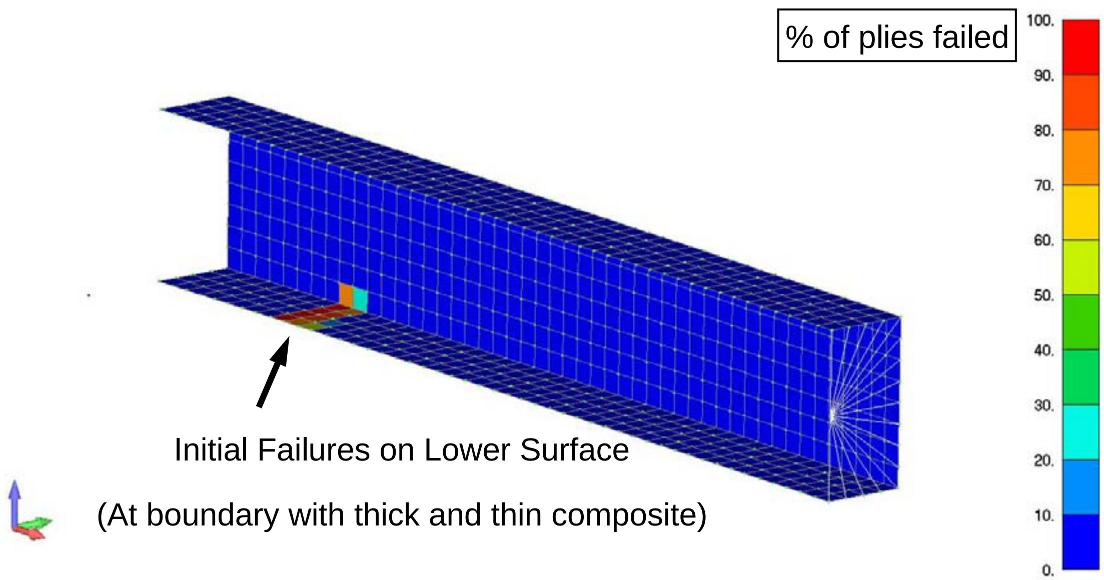
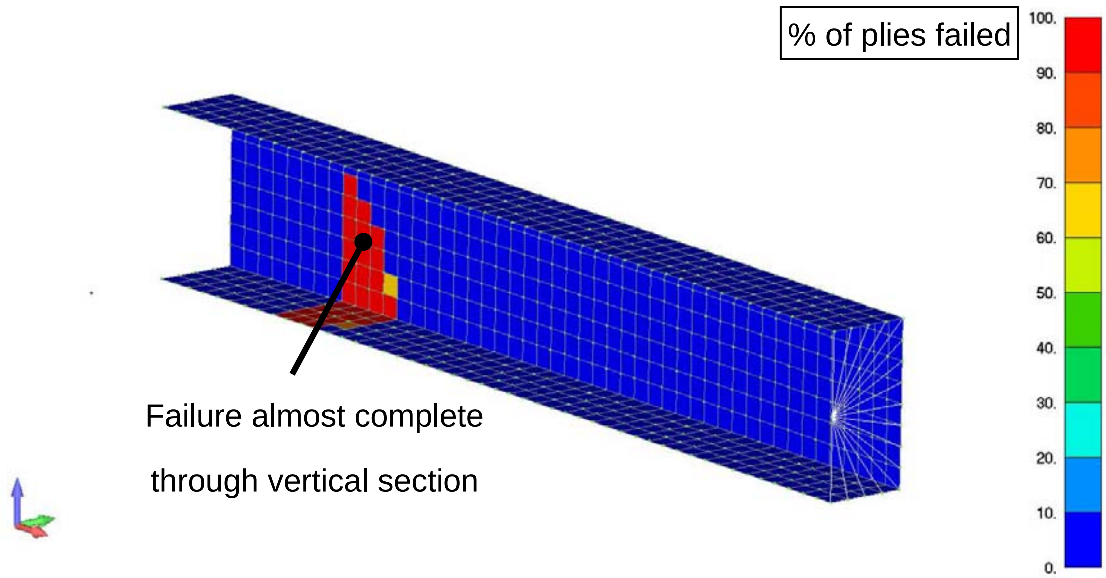
Evolution of Damage?

- First damage occurs on the lower flange
  - Low strength = compressive failures



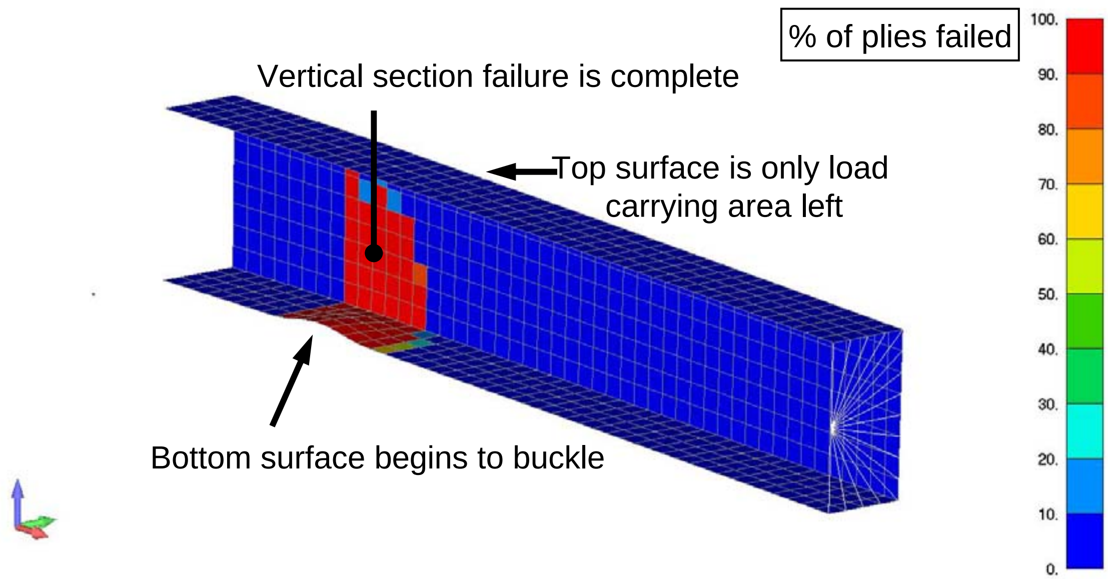
Evolution of Damage?

- Without the flange to carry the load, failure moves to the side walls



Evolution of Damage?

- All that is left is the top flange
  - Section begins to buckle



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Evolution of Damage.

- This model showed several interesting things
  - Quick compressive failure or plies
  - Redistribution of load to the side walls
  - Buckling once compressive strength gone
- While obvious for this model, the progression for a more complicated model might not be so.

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Conclusions

- A progressive failure analysis can provide many insights into the behavior of a laminated composite structure.
- Even for structures that are not intended to fail at all, it can be useful
  - Safety factors can be based on reserve loading capacity after FPF

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Conclusions

- Avoid Over Design
  - If safety factors too high
  - Wasted material, unnecessary weight
- Avoid Under Design
  - If safety factors too low
  - Potential for catastrophic failure