Sandwich Disbond No-Growth Evaluation

Energy-Based Analysis Approach and Applications

Supported by

Federal Aviation Administration

Wichita State University

Prepared for

Joint CMH-17-EASA-FAA Workshop on Sandwich Disbonding

Technical University of Denmark (DTU), Copenhagen, Denmark

June 20 -23, 2023

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Outline

- Background & Objectives
- Energy-Based Sandwich Disbond Analysis (ESDA)
- Benchmarking
- ESDA Implementation and Applications
- Conclusions and Future Work
- References

Introduction – Sandwich Disbond No-Growth Evaluation

Background

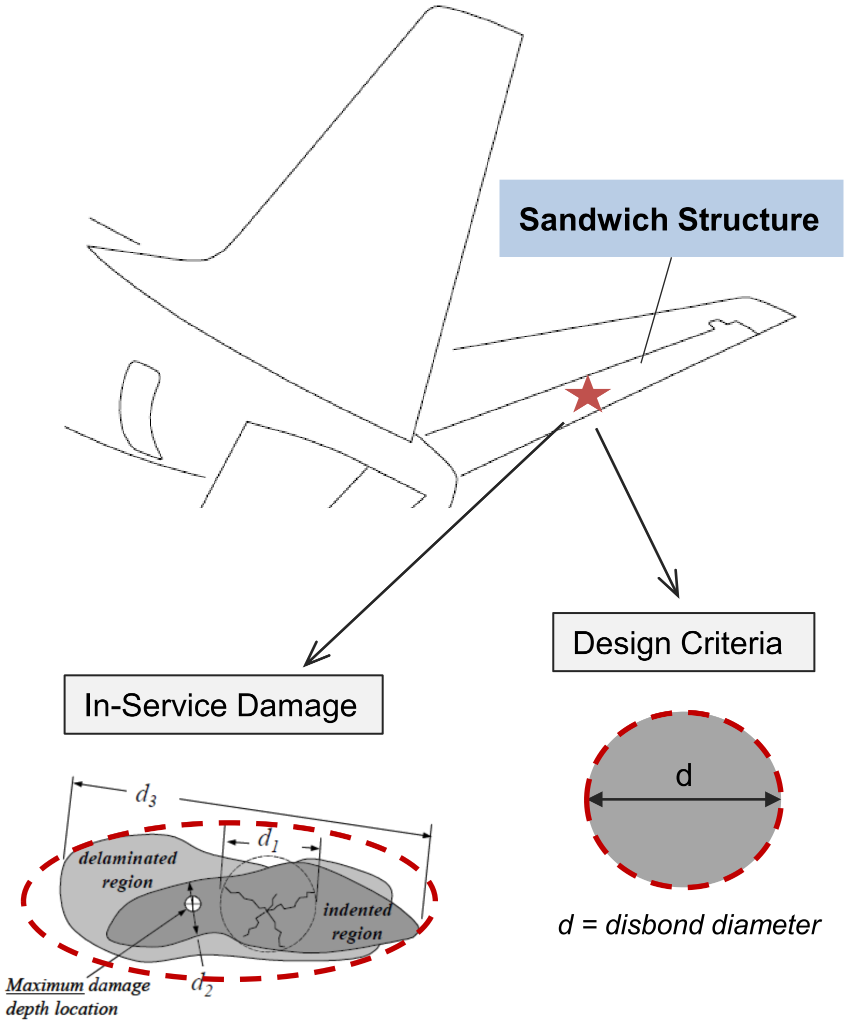
- CMH-17 Sandwich Disbond Task Group is working to develop and document analysis methods, test protocols, and design “best practices” to avoid growth of face sheet disbonds under static and fatigue loading, including pressure loading due to Ground-Air-Ground (GAG) cycles.

Motivation

- There is a need for an engineering approach for sandwich disbond evaluation that can rapidly predict the size of a disbond that will not grow under specified loading conditions.
  - *Approach should address both disbonds based on damage tolerance design criteria and associated with in-service damage.*

Approach

- Leverage previous work by NSE (for Boeing and Southwest Airlines) to develop an engineering approach using an energy-based solution together with conservative engineering assumptions to evaluate disbond no-growth.



Objectives and Approach

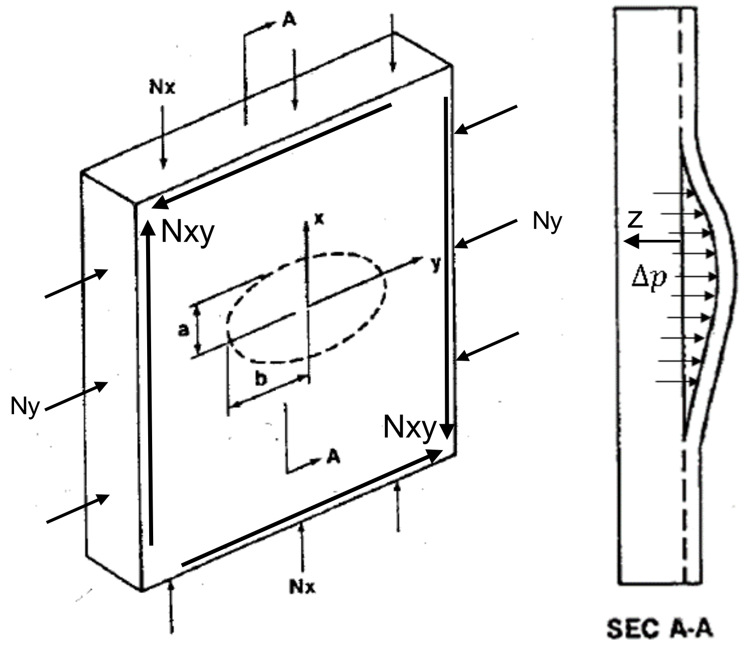
Engineering Analysis Approach Development

- Develop a sandwich disbond analysis method based on NSE's prior work as documented in the paper AIAA 2003-1596 [1]*.
- Modify the existing analysis method for static disbond growth to include pressure loading in addition to generalized in-plane loading.
- Validate the approach versus FE analysis and test results in collaboration with WSU, NASA, DTU and other research organizations and industry participants in the Sandwich Disbond Task Group.
- Demonstrate the engineering approach by performing sensitivity studies and developing example design curves using the developed analysis method.

Documentation

- Produce an FAA report with complete documentation of the engineering analysis approach.
- Develop content based on the above for inclusion in Volume 6, Chapter 4 of CMH-17, including documentation of the analysis method, example design curves, and assumptions used to "bound" the design space.

Generalized In-Plane Loads + Internal Pressure



*https://nsecomposites.com/damage-tolerance/damage-assessment-for-composite-sandwich-structure/

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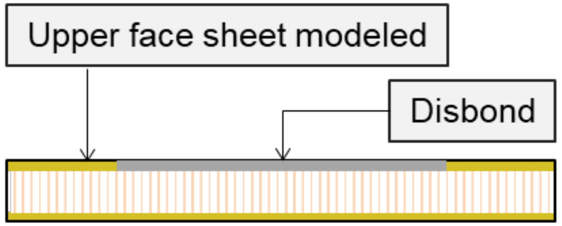
Overview

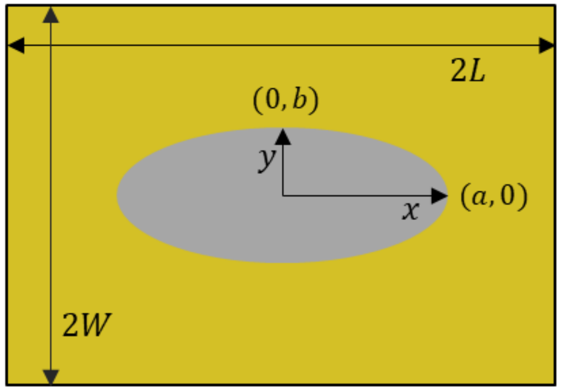
Physical System

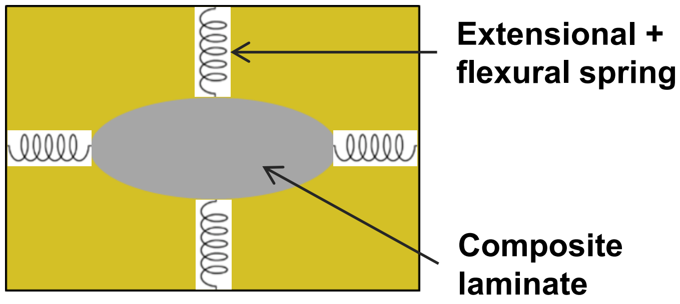
- Flat sandwich panel face sheet with an elliptical disbond.
  - *The disbonded region is modeled as a laminated plate.*
  - *The surrounding bonded region is modeled as a system of linear extensional and flexural springs.*
- Note that the core and backside face sheet are <u>not</u> explicitly modeled.
  - *Their effects are either conservatively ignored or addressed using suitable correction factors (see later slide).*

Theoretical Basis

- ESDA uses a seven-term Rayleigh-Ritz (R-R) formulation to model the physical system.
  - *The R-R formulation developed is the result of several studies, whose goal was to balance accuracy, performance and simplicity (ease of usage).*
- The R-R formulation uses classical plate theory with the von Karman strain-displacement equations for non-linear effects.
  - *A correction factor is used to address transverse shear effects (see later slide).*



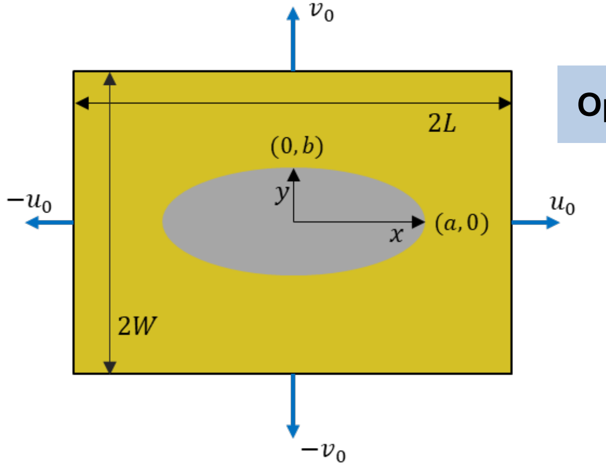




Loads

In-Plane Loading Options

- Option 1
  - *Prescribe face sheet edge displacements* u_0, v_0
    - Or do not prescribe for “free” edges.
- Option 2
  - *Prescribe sandwich panel loads* $Nx, \ldots, Mx, \ldots$



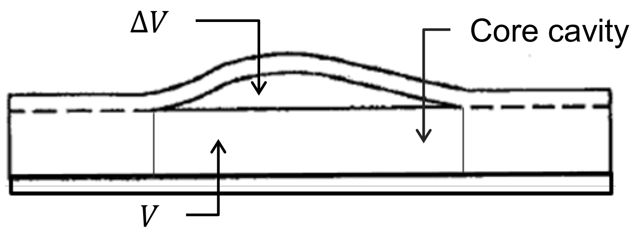
Option 1

Options Usage
- Option 1 to evaluate <u>test panels</u>.
- Option 2 to evaluate <u>design loads</u>.

Option 2

GAG Pressure

- Prescribe thermodynamic state of core cavity air both on ground and in flight.
- An approximation to the ideal gas law* is used to capture the effect of core cavity volume increase due to face sheet deformation, ΔV.
  - *A switch is provided to ignore the effect of* ΔV *for a more conservative result, or to simulate tests with constant pressure load.*

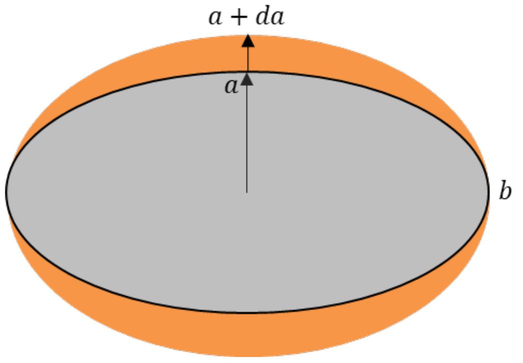


*See reference [2] for details

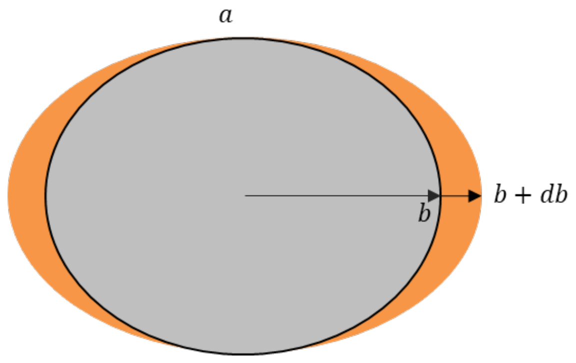
Calculating Energy Release Rates (Gs)

Step 1

- Use the R-R solution to calculate the total potential energy of the system with the elliptical disbond (a, b), Π.
- Repeat the procedure for elliptical disbonds $(a + da, b)$ and $(a, b + db)$, where da and db represent perturbations to a and b, respectively .
- Calculate Gs from the change $d\Pi$ in Π associated with the increase in disbond size.
  - *Two values, $G_{T,a}$ and $G_{T,b}$, as illustrated at right.*



Total G for growth in "*a*" direction, $G_{T,a} = -\frac{d\Pi}{\pi b da}$



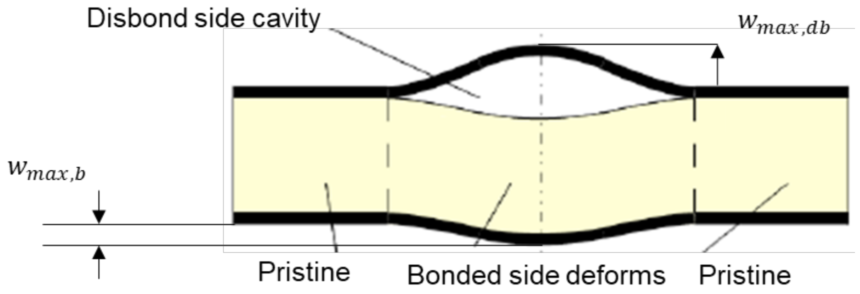
Total G for growth in "*b*" direction, $G_{T,b} = -\frac{d\Pi}{\pi a db}$

Total G vs. Peak G

- G_T is calculated for the types of growth depicted in the figures above.
- G_T is the decrease in panel potential energy per unit disbond growth area. It is not the critical location "peak" G.

Step 2

- Use correction factors to adjust for the effect of deformation of the face sheet opposite the disbond ("backside" displacement) and transverse shear.
  - $G_{ESDA,a} = C_{ts}C_{disp}G_{T,a}$ and $G_{ESDA,b} = C_{ts}C_{disp}G_{T,b}$
- A default of $C_{disp} = 2$ is used for the backside displacement correction factor and $C_{ts} > 1$ is calculated as described in [2].



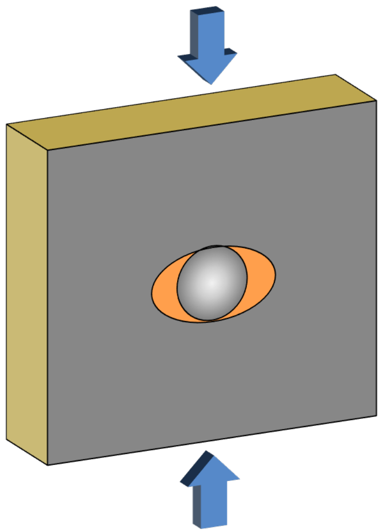
Disbond No-Growth Evaluation

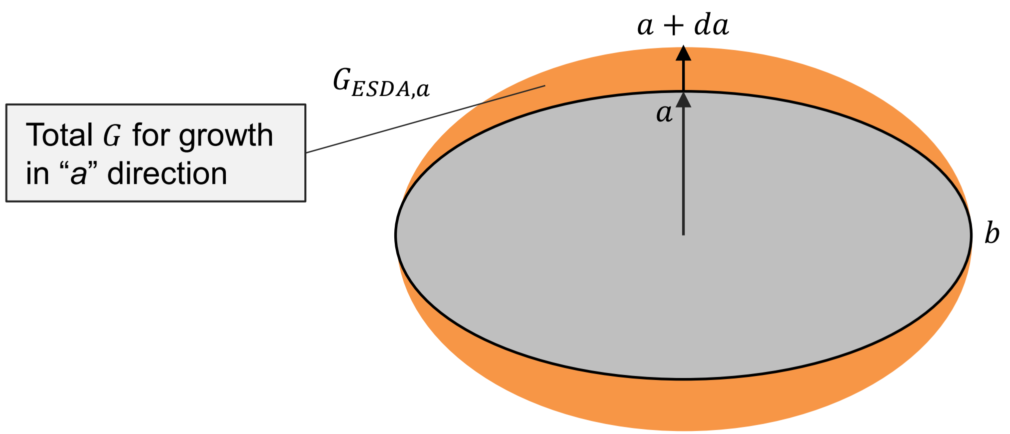
Static

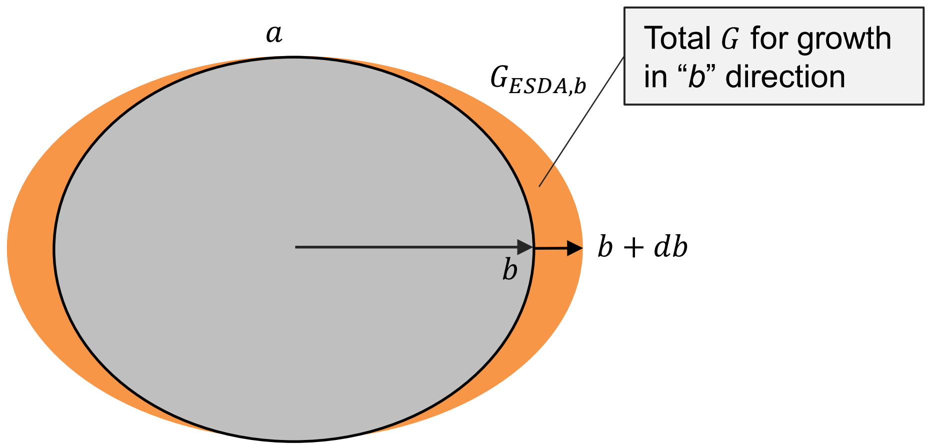
- The higher of the two calculated <u>total</u> Gs ($G_{ESDA,a}$ & $G_{ESDA,b}$) is compared with a critical fracture toughness (G_c) for the face sheet material.
  - *Choose the smallest G_c from all fracture modes, usually Mode I, G_{Ic}.*

Fatigue

- G_{thresh} data can be used (threshold growth value from da/dN test data).
  - *Choose the smallest G_{thresh} from all fracture modes, usually Mode I, $G_{I,thresh}$.*



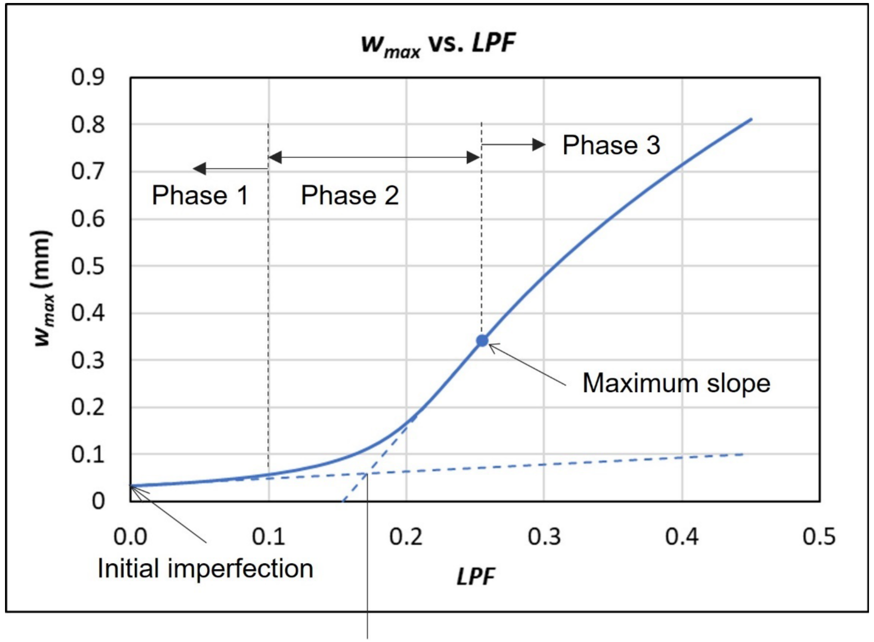




Recent Development – Estimating Critical Buckling Load

Non-Linear Response Characteristics

- For zero or negligible pressure load, a common response of the disbonded face sheet is illustrated in the figure.
  - *w_{max} is the maximum out-of-plane displacement, LPF is the scaling factor on the prescribed load.*
- Phase 1 is a quasi-linear "pre-buckled" phase; Phase 2 with an increasing w_{max} vs. LPF curve slope is a "buckling-dominated" phase; and Phase 3 with a decreasing w_{max} vs. LPF curve slope is the "membrane effect-dominated" phase.



Critical buckling $LPF = 0.1714$

Calculating Critical Buckling Load

- The critical buckling load is obtained from the intersection of the two tangent lines to the w_{max} vs. LPF curve displayed as dashed blue lines in the figure.
  - *The line from the left is the tangent at $LPF = 0$*
  - *The line from the right is the tangent at the curve's maximum slope point.*
- Prescribed pressure loads are ignored when calculating buckling load.

Initial imperfection may be due to a manufacturing defect or simply a very small w_{max} that is within manufacturing tolerances.

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FE Data Sources

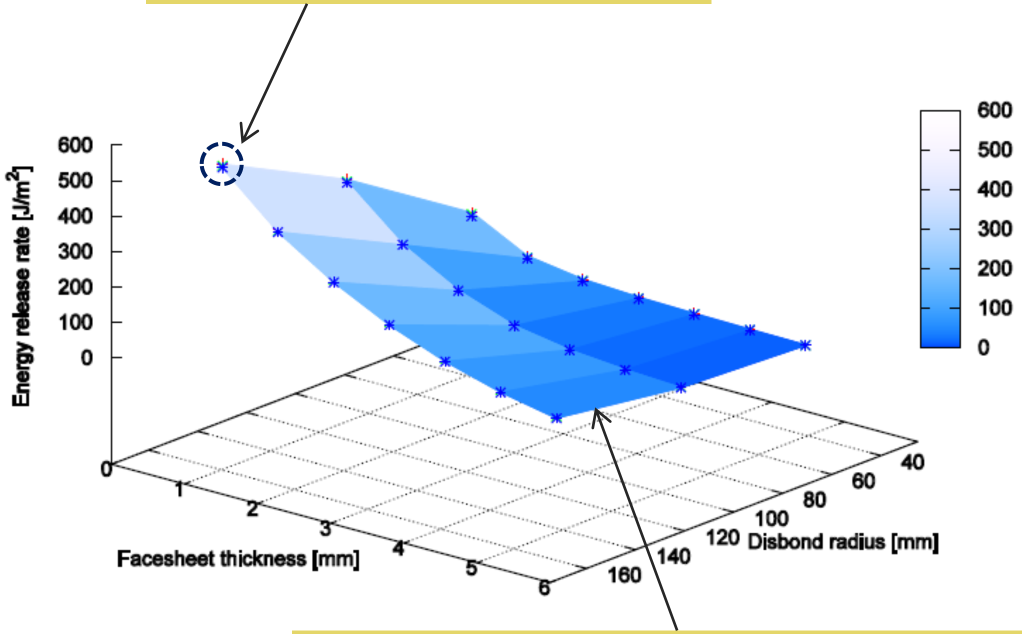
Rinker et al. [3]

- Evaluated multiple configurations spanning 7 face sheets, 3 disbond radii, and many Hexcel HRH-10 core configurations.
- Only loading applied was GAG pressure via the ABAQUS fluid cavity pressure loading feature.
- Calculated energy release rates and the effect on energy release rates of pressure reduction due to outward displacement of the disbonded region of the face sheet.

Chen et al. [4]

- Evaluated the critical (highest energy release rate) Rinker [3] configuration for three load conditions.
  - *GAG pressure load only*
  - *Uniaxial in-plane load only*
  - *Combined in-plane and GAG pressure loads*

Chen benchmark configuration:
76.4 mm thick HRH-10 ⅛ 3.0 core



Rinker benchmark configurations (21):
carpet plot for 25.4 mm thick HRH-10 ⅛ 1.8 core

Total energy release rate (G_T) carpet plots from Rinker [3]

Rinker/Chen – Model Description

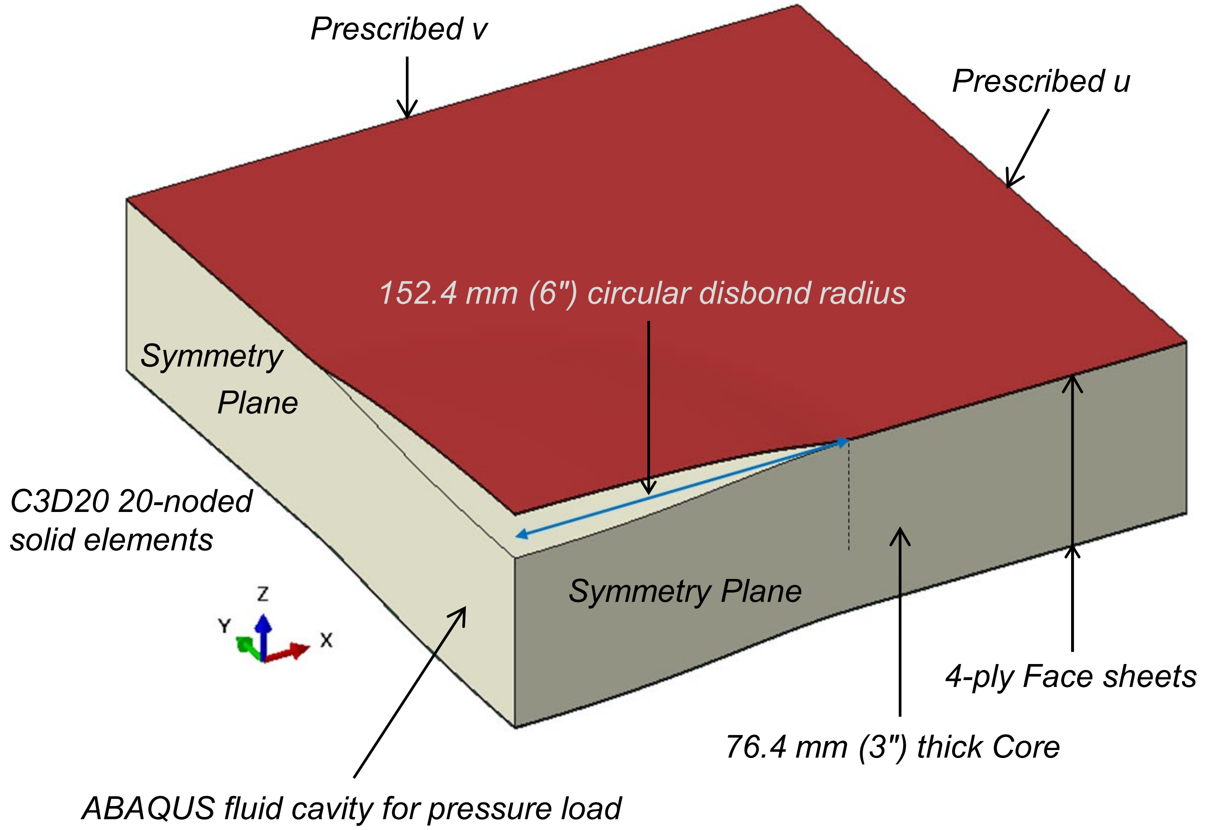
Model Attributes

- Circular disbond in upper face sheet centered in square sandwich panel with sides twice the disbond diameter.
- Biaxial symmetry enforced (1/4 model).
- Loads
  - *GAG pressure using the ABAQUS fluid cavity feature*
  - *Prescribed panel edge displacements (Chen only)*
- 20 node reduced integration elements
- Seven face sheets with CYCOM 5320 PW plies, three disbond radii and three core types (Rinker only)
  - *Chen evaluated the critical configuration (see below).*

Example – Rinker/Chen Configuration

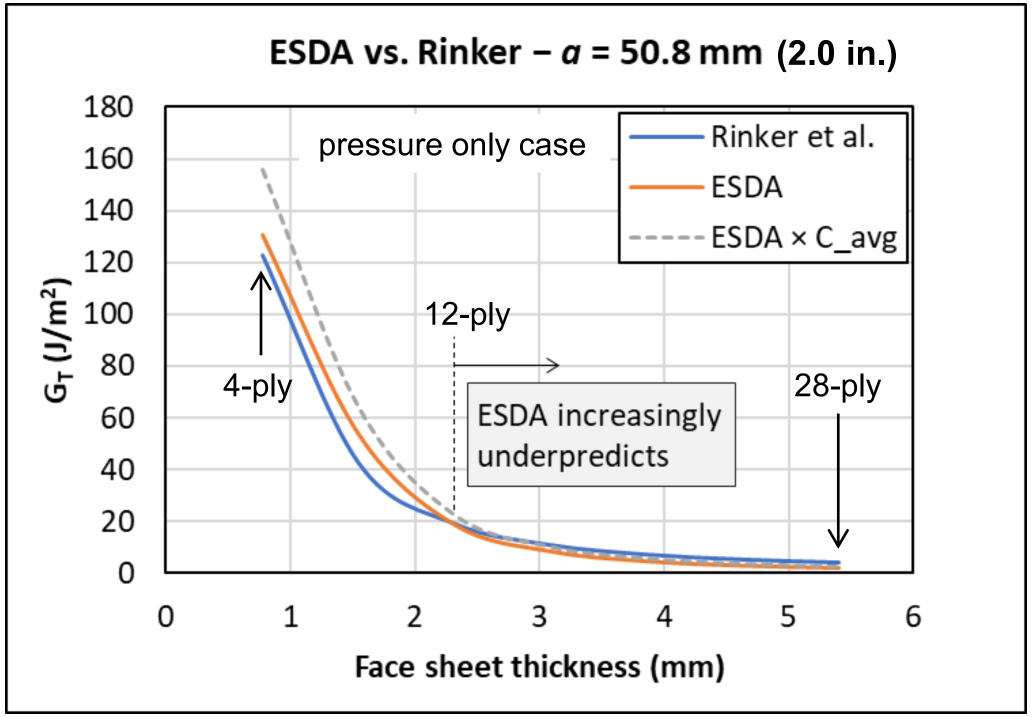
- 152.4 mm (6") disbond radius
- 4-ply face sheets
- 76.4 mm (3") thick “HRH-10 ⅛ 3.0” core

FE Model Schematic – Rinker/Chen Configuration from [3] and [4]



Ply material: CYCOM 5320 PW [3]

ESDA vs. Rinker – Energy Release Rates (*a* = 50.8 mm)



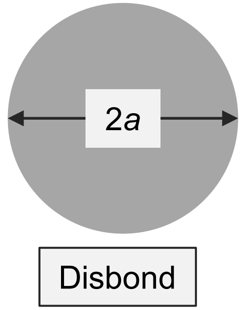
Note about C_{avg}

- A correction factor of $C_{avg} = 1.19$ was estimated using ad hoc FE models (see [2]), to account for the ESDA weighted average vs. Rinker peak G_T discrepancy.

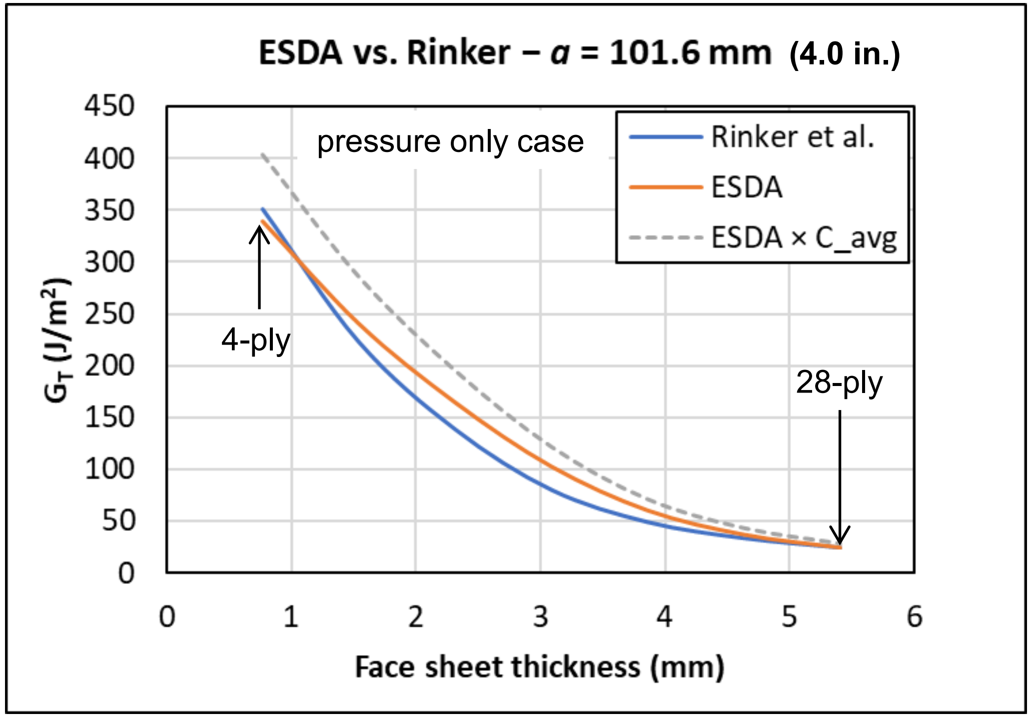
Results Discussion

- Total energy release rate (G_T) predictions are slightly higher than Rinker for thin face sheets.
- The 12-ply face sheet configuration represents a transition point beyond which increasing underprediction occurs. However, the $G_T s$ for these configurations are very small. See earlier slides for displacements of 12- and 28-ply cases.
- Using a correction factor, $C_{avg} = 1.19$, provides an extra cushion (dashed gray lines), but does not appreciably reduce underpredictions for the high face sheet thickness-to-disbond size configurations.

Note that the poor predictions for the **high thickness-to-disbond size** ratio configurations may be due to a combination of a stiff rotational BC at the face sheet edges ($\frac{\partial w}{\partial x} = \frac{\partial w}{\partial y} = 0$) and a low transverse shear correction factor. This issue will be studied as part of Limits of Applicability (LoA) development.



ESDA vs. Rinker – Energy Release Rates (a = 101.6 mm)



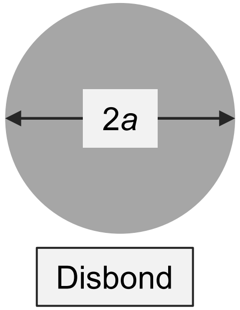
Note about C_{avg}

- A correction factor of $C_{avg} = 1.19$ was estimated using ad hoc FE models (see [2]), to account for the ESDA weighted average vs. Rinker peak G_T discrepancy.

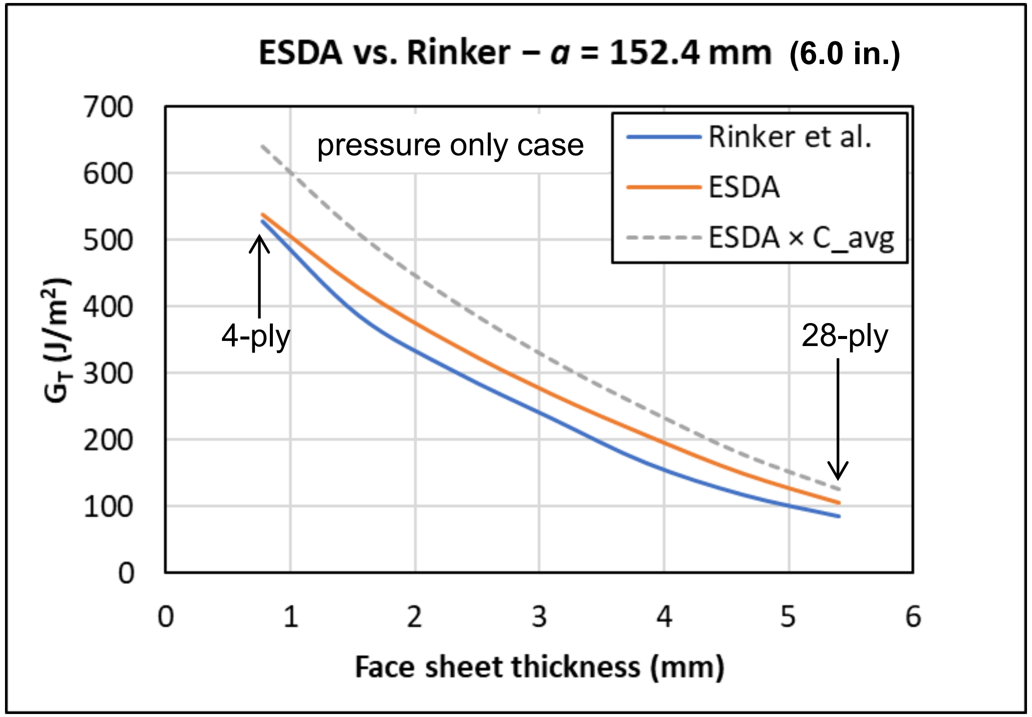
Results Discussion

- Total energy release rate (G_T) predictions are mostly slightly higher than Rinker.
- ESDA slightly underpredicts for the thinnest and thickest face sheets. This is because ESDA predictions are less sensitive to face sheet thickness variations than the FEA predictions.
- Using a correction factor, $C_{avg} = 1.19$, provides an extra cushion (dashed gray lines), but is only useful for the 4-ply and 28-ply face sheets.

Note that the tendency for **ESDA predictions to be less sensitive to face sheet thickness than FEA** predictions is also observed for the 152.4-mm disbond radius configurations (see next slide). This issue will be studied as part of LoA development.



ESDA vs. Rinker – Energy Release Rates (a = 152.4 mm)



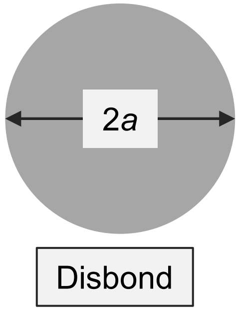
Note about C_{avg}

- A correction factor of $C_{avg} = 1.19$ was estimated using ad hoc FE models (see [2]), to account for the ESDA weighted average vs. Rinker peak G_T discrepancy.

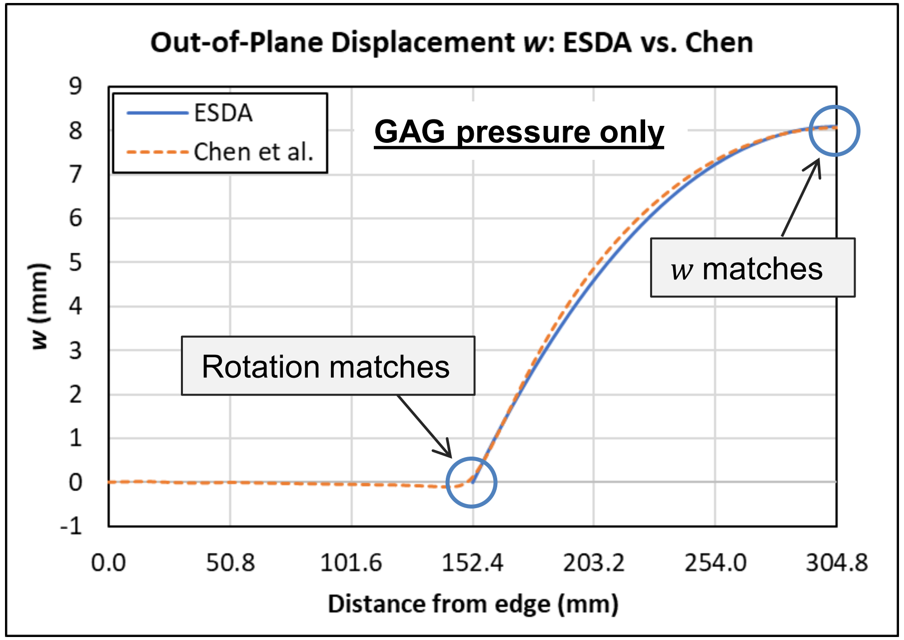
Results Discussion

- Total energy release rate (G_T) predictions are slightly higher than Rinker. Note that like the 101.6-mm disbond radius configurations, ESDA predictions are less sensitive to face sheet thickness variations than the FEA predictions, particularly for thin and thick face sheets.
- Using a correction factor, $C_{avg} = 1.19$, provides an extra cushion (dashed gray lines), but is unnecessary because it makes the predictions too conservative.

Note that **ESDA results are generally good (~10% higher G_T)** but the tendency for ESDA predictions to be less sensitive to face sheet thickness than FEA will be studied as part of LoA development.



ESDA vs. Chen Displacements – Load Cases with Pressure

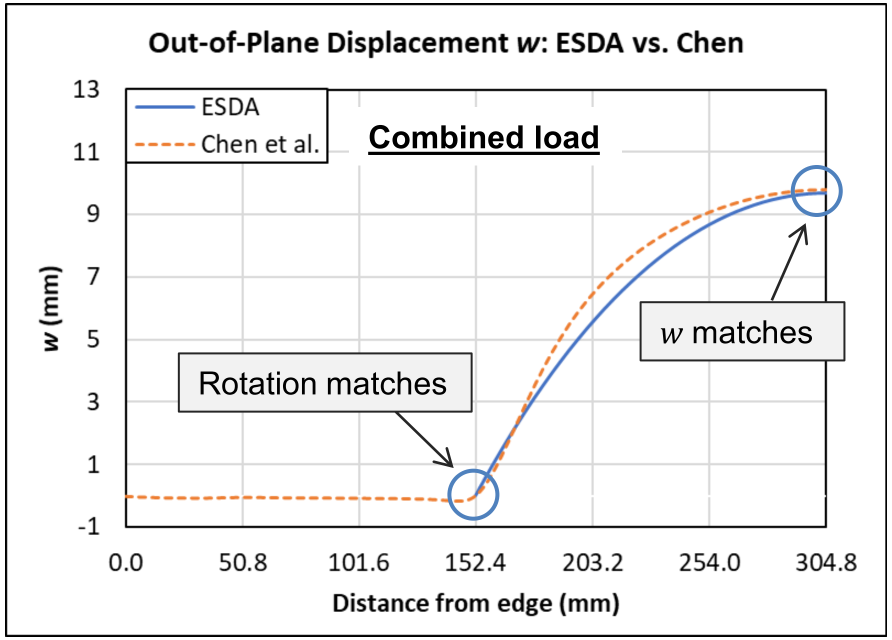


Results Summary

- Excellent correlation

Loads

- GAG cycle pressure – 12,200 m altitude – with pressure-deformation coupling turned ON (both figures)
- Nominal strains $\varepsilon_x = -0.002, \varepsilon_y = 0$ (right side figure only)

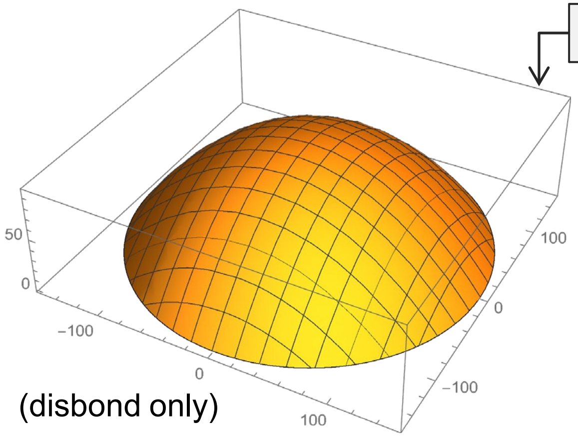


Results Discussion

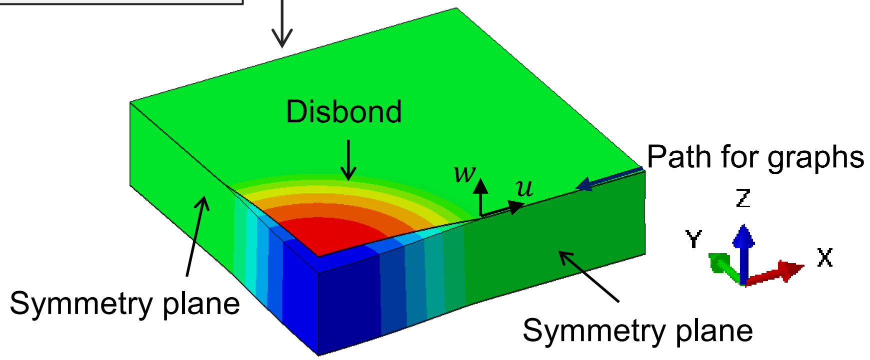
- Elastic restraints perform well, predicting $\frac{\partial w}{\partial x}$ at the disbond edge (152.4 mm) accurately.
- The simple functional form used for w closely matches the predicted FE response.
- The ESDA deformed shape and FE contour plots shown here for the combined load case are similar for the pressure-only load case.

ESDA, 10X magnification

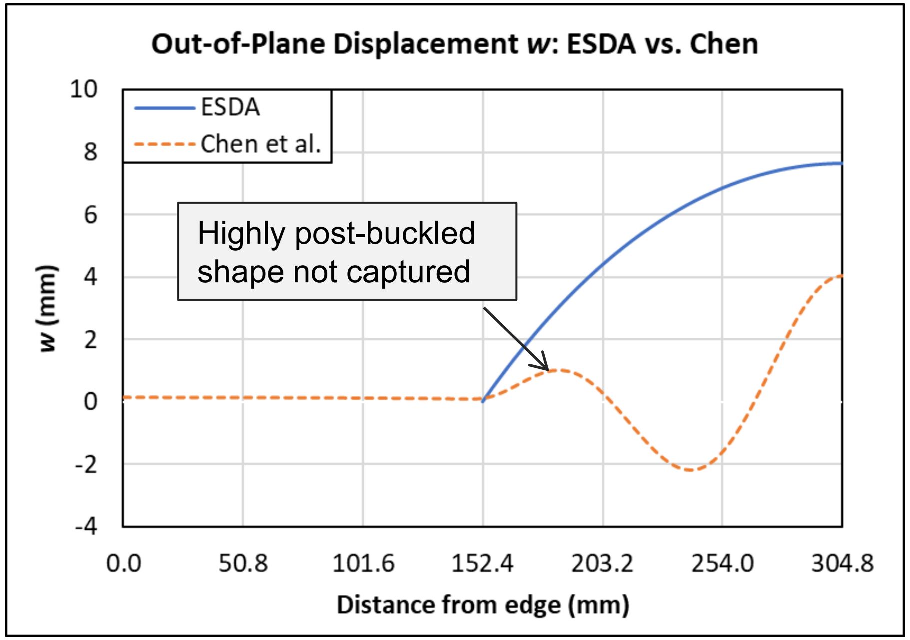
Combined load



(disbond only)



ESDA vs. Chen Displacements – In-Plane Load Only Case

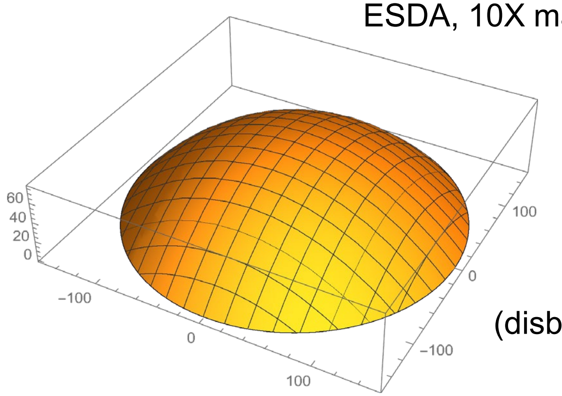


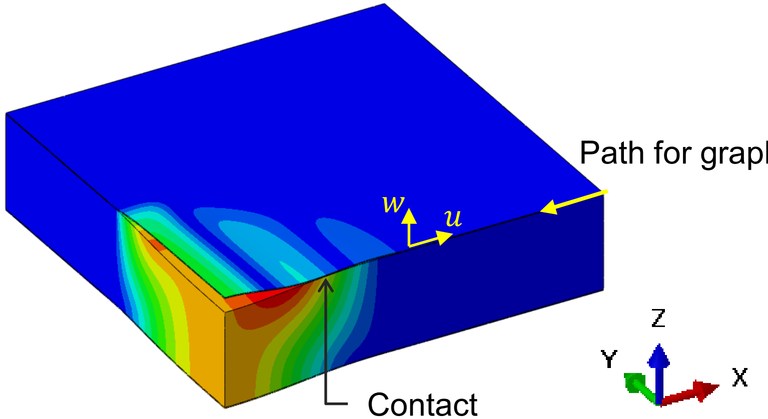
Results Summary

- Poor correlation
- Address with Limits of Applicability (LoA)

Load

- Nominal strains $\varepsilon_x = -0.002, \varepsilon_y = 0$





Factors Contributing to Poor Correlation

- Configuration is highly post-buckled (post-buckled ratio ~50) due to large disbond size and thin face sheet.
- Displacement functions are not rich enough to describe the complex, buckled shape of the face sheet.
- The face sheet opposite the disbond, which also buckles, is not modeled.
- Disbond-to-core contact is not modeled.

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ESDA vs. NIAR – Benchmarked Configurations*

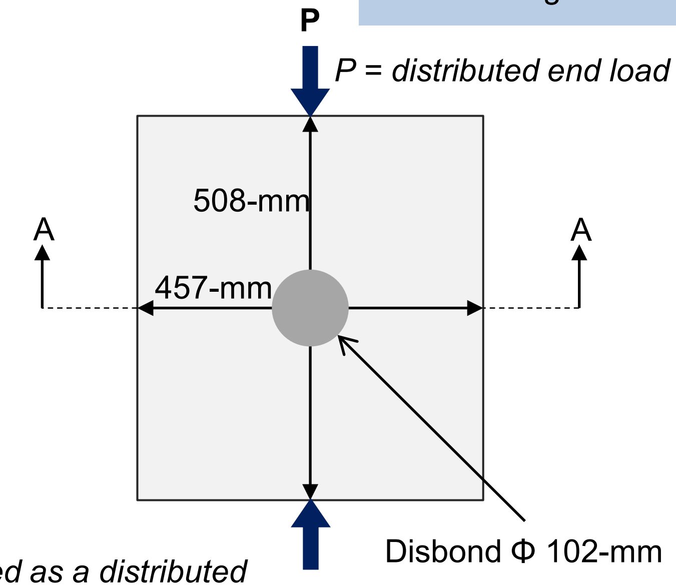
Description

- Face Sheets and Core
  - *<u>Face sheet</u>: 8-ply + <u>core</u>: 12.7-mm thick, 96 Kg/m^3 dense & 3.2-mm cell size.*
  - *<u>Face sheet</u>: 4-ply + <u>core</u>: 12.7-mm thick, 48 kg/m^3 dense & 9.5-mm cell size.*
  - *Ply material: Cytec 5320-T650 plain weave prepreg [6]*
- Panel and Disbond Dimensions
  - *Panel size 508-mm × 457.2-mm*
  - *Circular disbond with radius of 50.8-mm*

Loads

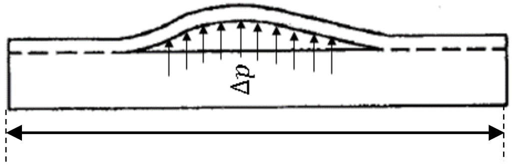
- Apply uniaxial compression load, P. Determine maximum P, P_{crit}.
- 0.09 MPa internal pressure (Δp)

Panel Configuration



P is applied as a distributed panel load in ESDA

Section A-A



$\Delta p = 0.09\ MPa$

Note

- NIAR also performed detailed, high-fidelity FEA, and these FEA results were also benchmarked.

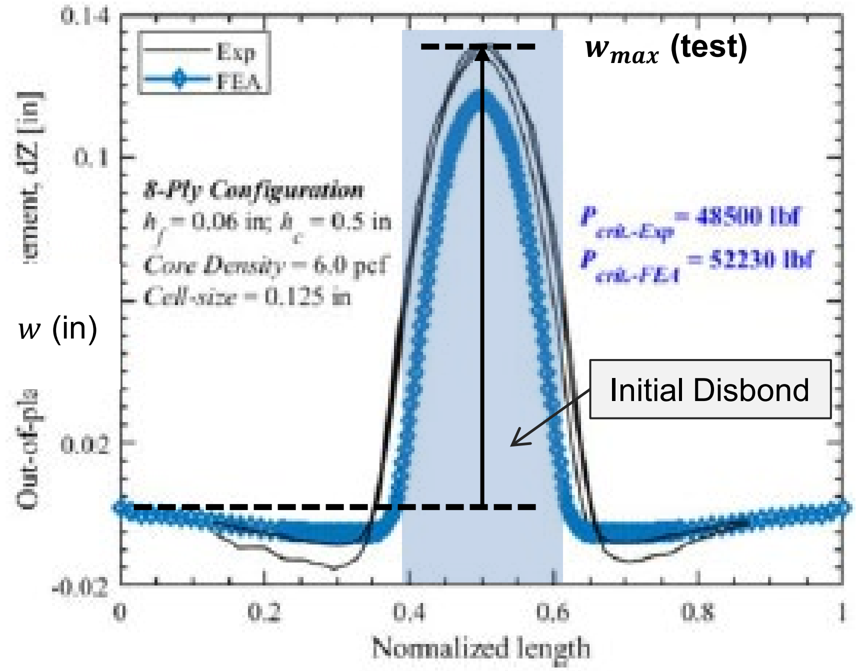
**Per discussions in 2020 with Vishnu Saseendran and data from [5, 6]*

ESDA vs. NIAR – Benchmarked Results

Displacements

- Maximum out-of-plane displacements, w_{max}.

Out-of-Plane Displacement (w) for 8-ply configuration [6]



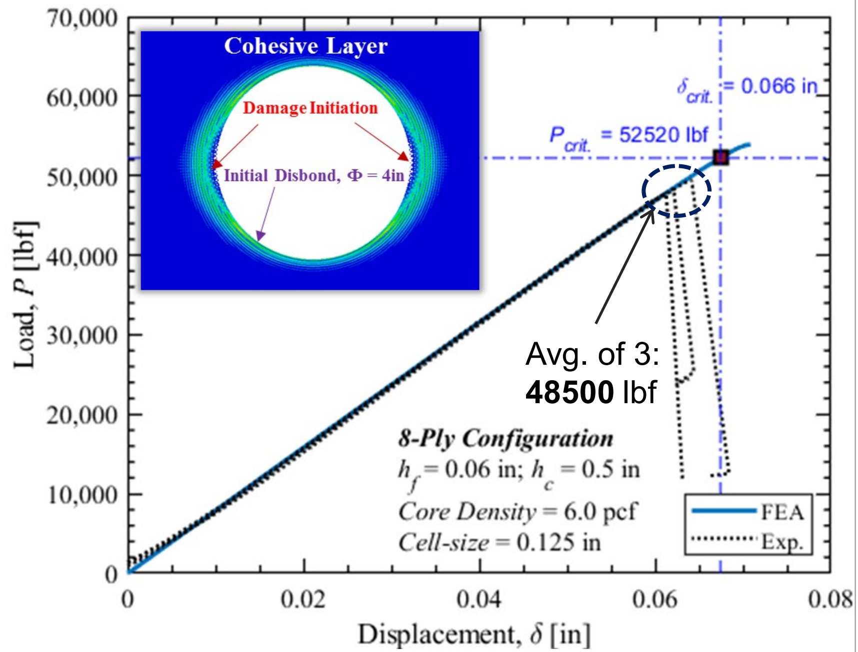
Critical Loads, P_{crit} (Failure Load)

- ESDA needs a fracture toughness value (G_c) to predict P_{crit}. G_c data was obtained from [5]:
  - *For the FEA, the G_c data used for each configuration was provided.*
  - *For the test panels, ESDA used SCB test data reduced using MBT.*

Plies	G_c (J/m^2)	
	FEA	Test
4	800	545
8	1400	1770

Similar results for 4-ply configuration

Critical Load (P_{crit}) for 8-ply configuration [6]



ESDA vs. NIAR – Results

Maximum Out-of-Plane Displacements, w_{max}

- ESDA is within 6% of the NIAR (Seneviratne et al. [6]) FEA predictions and within 12% of the test results.

Critical Loads, P_{crit}

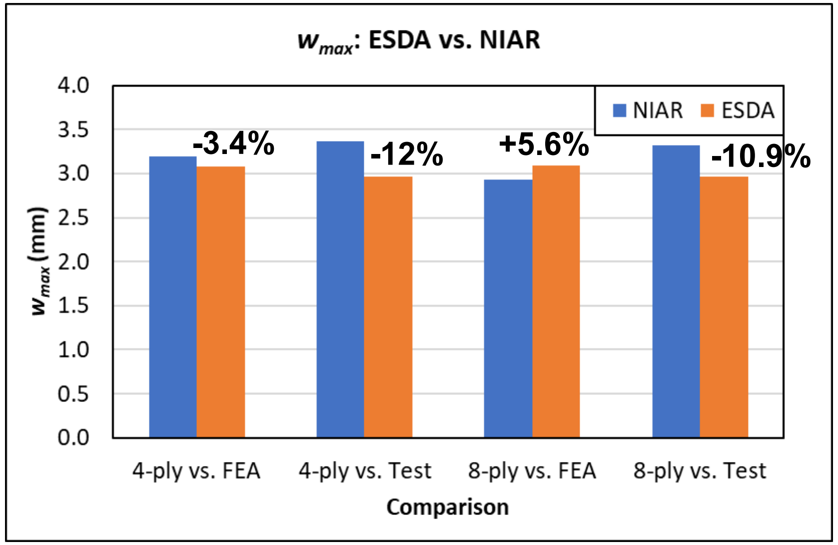
- ESDA is < 6% lower than the NIAR FEA predictions.
- ESDA does not correlate as well with test data*.
  - *Underpredicts by almost 30% for the 4-ply face sheet configuration (conservative)*
  - *Overpredicts by 15% for the 8-ply face sheet configuration (unconservative)*

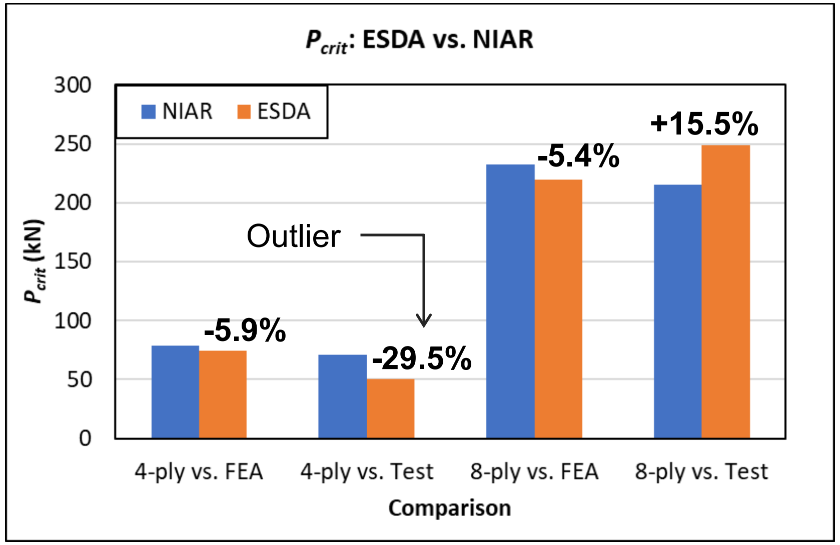
Notes on ESDA Settings

- Pressure-deformation coupling was set to OFF since pressure was applied directly in the test and the FEA did not include coupling.

Results Summary

- Generally good correlation





*Need to consult with NIAR to ascertain whether G_c values used for test P_{crit} calculations were appropriate.

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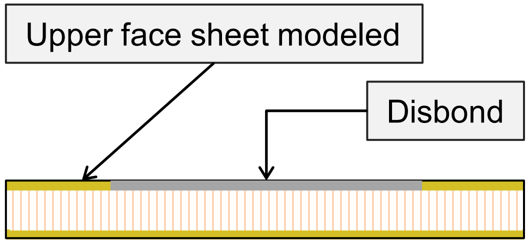
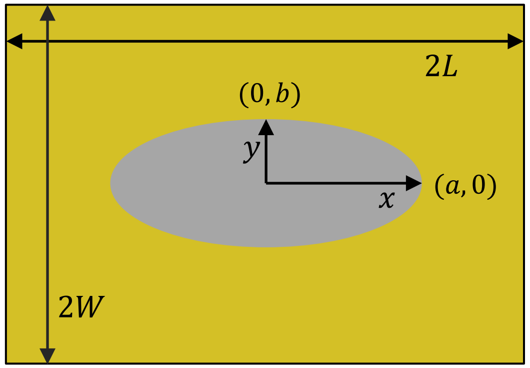
Implementation – Spreadsheet Tool

User Interface

- NSE Composites has implemented ESDA as a Microsoft Excel workbook (“ESDA Tool”).
  - *For additional information, see Reference [2].*
- The ESDA tool was used in some of the benchmarking studies in the previous section and to demonstrate ESDA applications in this section.





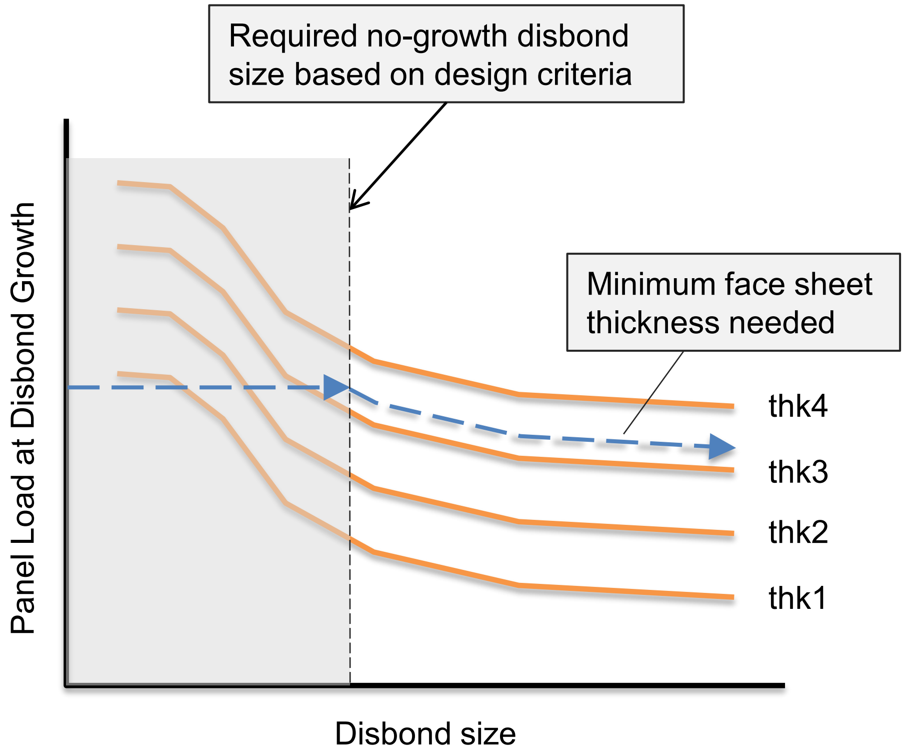
Mode of Operation

- User prescribes inputs in designated worksheet cells.
- User-defined functions send inputs to the Rayleigh-Ritz solver, which returns the solution.
  - *Solver calculations are implemented in a dynamic link library (*.DLL) that is coded in Fortran.*
- Results are displayed in the Excel workbook in tabular and graphical form.
  - *Energy release rates, estimated critical buckling load, displacements at selected locations, and sandwich panel and face sheet **ABD** matrices (tabular)*
  - *Disbond no-growth design curves and displacement graphs along user-defined paths parallel to the disbond x and y axes (graphical)*
  - *Buckling onset curves to evaluate buckling relative to disbond growth (graphical).*

Engineering Usage for Disbond No-Growth Analysis

Engineering Design Curves

- Curves of load versus disbond size can be developed based on predictions at varying load levels.
- Carpet plots can then be developed using multiple curves for a range of a specific design variable as shown in the figure.
- Design criteria might include a required no-growth disbond size (e.g., for defects and/or allowable damage).
- For a given applied load, the minimum thickness can be determined.



Extension to Multiple Variables

- Response surfaces could be developed using analyses covering the design space and range of applied loads.
- The key design variables would be addressed in equation form.
  - *Face sheet stiffness and/or orthotropy*
  - *Face sheet thickness*
  - *Disbond size and aspect ratio*
  - *Biaxial loading ratio, pressure*

Example Engineering Design Curves (1 of 2)

Design Variable for Carpet Plots

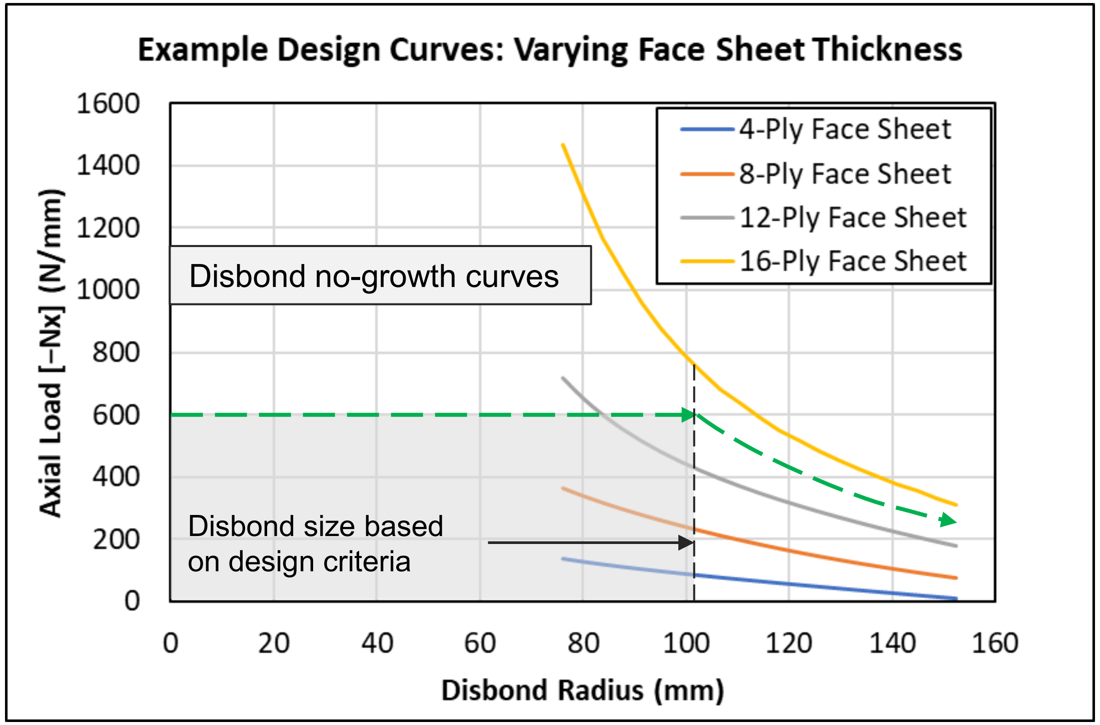
- Face sheet thickness

Key Values

- Nx = variable
- Δp = 0.57 atm (12,200 m)
- G_c = 443 J/m^2

Variation of G_c

- These curves assume G_c is constant. Typically, G_c varies with face sheet and core properties.
- The example on the next slide uses G_c as the design variable for the carpet plots.



Discussion

- The family of curves in the chart shows how the maximum size of disbond that is not predicted to grow varies for different face sheet thicknesses with axial compression loading, at an altitude of 12200 m.
- For example, if the sandwich panel load is $Nx = -600$ N/mm, the number of face sheet plies needed to satisfy the design criterion of a 101.6-mm (4") minimum disbond radius is ~14 plies.

Example Engineering Design Curves (2 of 2)

Design Variable for Carpet Plots

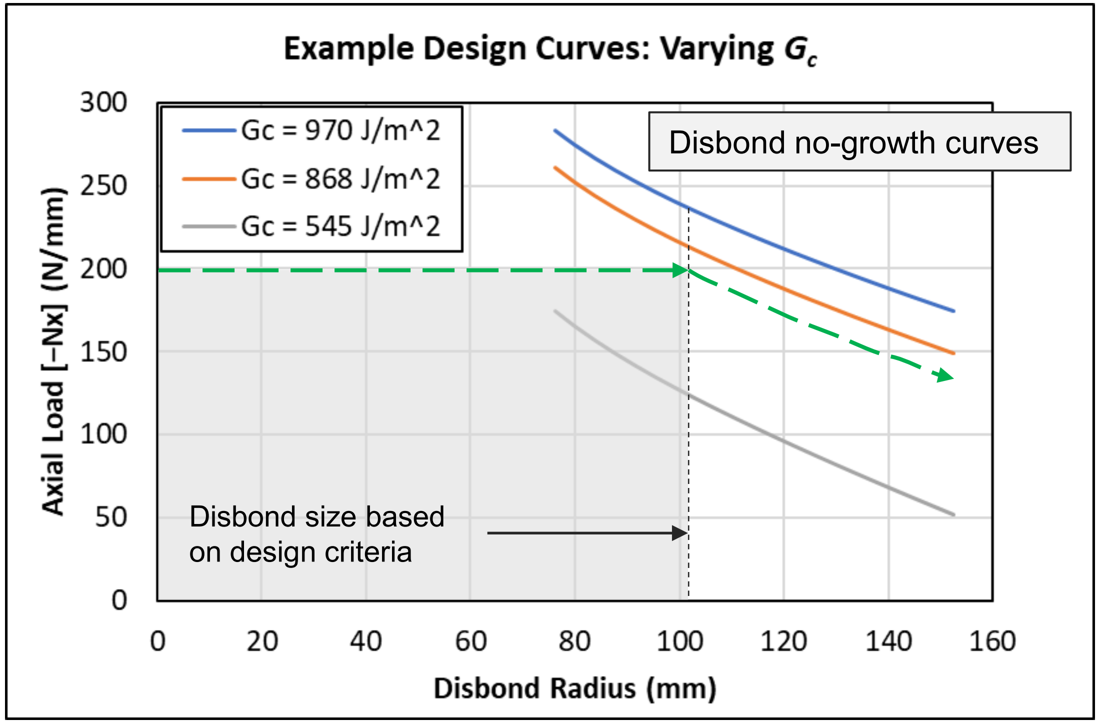
- Equivalent fracture toughness, G_c

G_c Data from NIAR [5]

NIAR Data			
Core Properties			G_c (J/m^2)
Thickness (mm)	Cell Size (mm)	Density (Kg/m^3)	
12.7	3.2	96	970
25.4	3.2	48	868
12.7	9.5	48	545

Key Values

- Nx = variable
- Δp = 0.57 atm (12,200 m)
- 4-ply face sheet



Discussion

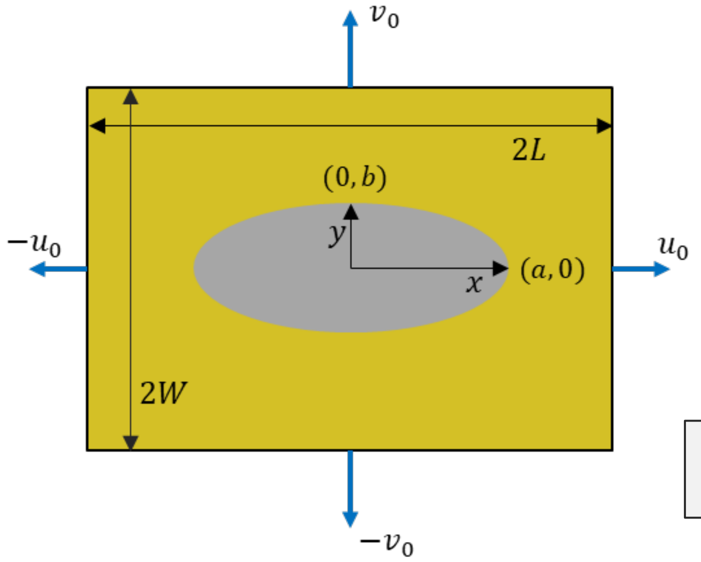
- The family of curves in the chart shows how the maximum size of disbond that is not predicted to grow varies for different fracture toughnesses with axial compression loading, at an altitude of 12200 m.
- For example, if the sandwich panel load is $Nx = -200$ N/mm, the fracture toughness needed to satisfy the design criterion of a 101.6-mm (4") minimum disbond radius is ~825 J/m^2.

Example Buckling Output

Tabular – Critical Buckling Load

ε x	ε y	Nx	Ny	Nxy	Mx	My	Mxy
-0.000025	0.000000	---	---	---	---	---	---

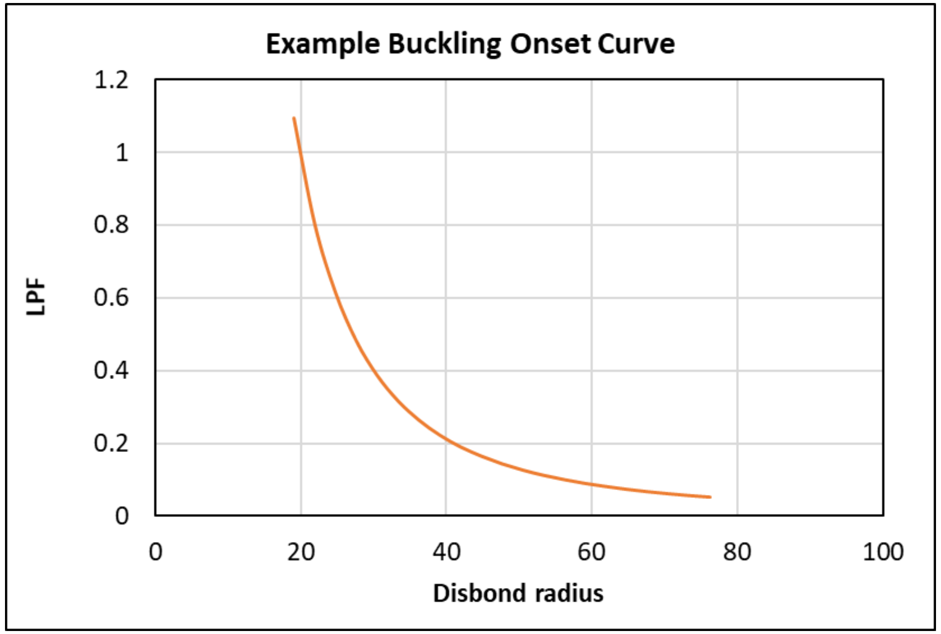
- In this example, Option 1 was used for loads, hence the critical buckling load is reported as nominal face sheet strains $\varepsilon_x, \varepsilon_y$.
- If Option 2 is used, the critical buckling loads will be reported as sandwich panel running loads N_x, ...



Prescribed nominal strains are u_0/L and v_0/W

Graphical – Buckling Onset Curve

- Akin to the design curve, the buckling onset curve plots the buckling load as a scale factor (LPF) on the prescribed load in the ESDA tool vs. the radius of a circular disbond.
  - *For Load Option 1, LPF scales the prescribed nominal strains; for Load Option 2, LPF scales prescribed panel N_x, ...*



Outline

Background & Objectives

Energy-Based Sandwich Disbond Analysis (ESDA)

Benchmarking

ESDA Implementation and Applications

Conclusions and Future Work

References

Conclusions

ESDA vs. FE Benchmarks

- Overall, very good correlation was observed.
- For a small number of benchmarks, correlation was poor.
  - *Such cases should be clearly identified as being outside the Limits of Applicability (LoA) of ESDA.*
  - *Additional studies and benchmarking can be used to set well-defined LoA, which*

ESDA vs. Test Data

- Overall, good correlation was observed vs. available data.
  - *Available data, however, was very limited; additional benchmarking vs. test data is needed.*

ESDA Implementation and Applications

- ESDA has been implemented as a versatile tool that rapidly generated very useful output for the designer.
  - *Displacements in the disbond, energy release rates, disbond growth prediction, design curves and buckling information*
- The design curve feature of the ESDA tool can be used to easily generate families of design curves.
- The ESDA tool can be calibrated vs. sandwich test panel DIC data to estimate effective fracture toughness.

Future Work

Limits of Applicability (LoA) Development

- Well-defined LoA are important for effective use of a simplified approach such as ESDA.
- Some work to support this is in progress …
  - *Criteria to identify core-face sheet contact*
  - *Methods to "extrapolate" the total energy release rates that ESDA calculates to estimate the local maximum energy release rate along the edge of the disbond.*

ESDA Improvements

- Target simple, value-added improvements first, then more advanced improvements based on continuing ESDA benchmarking and evaluation, as well as industry feedback.
  - *The recent addition of buckling predictions to ESDA is a result of industry-driven feedback.*

Longer-Term Objectives

- Evaluate the feasibility of extending ESDA to <u>variable and shear-dominated loading</u>.
- Consider adding capability for <u>curved sandwich panels</u>.
- Consider how ESDA might be applied to structural details.
  - *For example, core ramps*

Collaboration and Documentation

- Continue working with Sandwich Disbond Growth team members DTU and WSU/NIAR.
  - *Supports ESDA improvements by providing crucial data for LoA development and benchmarking*
- Work with industry partners.
  - *Supports ESDA improvements by providing data for benchmarking and information that can be used to tailor ESDA to industry needs.*
- Develop content for CMH-17: <u>best practices</u>, pertinent <u>sandwich disbond examples</u>, sample <u>design curves</u> and <u>sensitivity studies</u> for a range of design parameters.

Outline

Background & Objectives

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References

References

1. Walker, Thomas H., Douglas L. Graesser, Stephen H. Ward, Joseph F. Floyd, Hamid Razi and Vangelis Ploubis, “Damage Assessment for Composite Sandwich Structure”, AIAA Paper 2003-1596, 44th AIAA/ASME/ASCE/AHS SDM Conference, April 2003.
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6. Seneviratne, Waruna, Shenal Perera, Vishnu Saseendran and Pirashandan Varatharaj, “Analysis & Validation of Damage Growth in Aircraft Sandwich Structures under Combined Loading: An Engineering Approach”, FAA-EASA Sandwich Disbond Workshop, Copenhagen, Denmark July 9-10, 2019.