



Quasi-Static and Dynamic Analysis of Composite Panels: Challenges in Engineering-Level Commercial Software

2020 ASC 35

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Overview



- Introduction and Objective
- Experimental overview
- FE models (C-channel and corrugated panel)
- Results (quasi-static)
 - Parametric study summary
 - Load/displacement and Failure Patterns for both C-channel and corrugated panels
- -Results (dynamic)
 - Load/displacement and Failure Patterns for both C-channel and corrugated panels
- Conclusions and lessons learned



Introduction

- Building a reliable numerical model for an engineering-level analysis of quasi-static and dynamic crushing response in composite structures is a **challenging** task
- A robust, reliable and predictive material model should be able to reproduce experimental results reasonably well irrespective of composite geometry.
- Commercially available codes with a built-in composite model that are typically used by the engineering community, include:
 - LS-DYNA
 - ABAQUS Explicit
 - RADIOSS
 - PAM-CRASH
- Most of these numerical models utilize **damage initiation, damage propagation, and failure criteria** based on **physical** (*experimentally measurable*) and **non-physical** (*model dependent*) **parameters**.
- Typically, conducting **parametric studies** on both physical and non-physical model parameters is crucial in understanding the influence of these properties on the numerical response.



Problem Description and Objective

During **collaboration** with Honda America R&D: (Space-Act agreement (SAA3-1304)

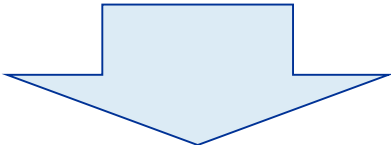
- Given preliminary quasi-static impact simulations conducted by Honda R & D (**LS-DYNA (MAT-58)**) showed: **Material parameter set used needed to be extensively modified for different geometries** in order to successfully reproduce experimental results.



Asked

Two Questions:

- a) Will we face the same issue repeating the same problem in another commercial software, e.g. ABAQUS ?
- b) IF so, can we obtain a set of unique **geometry-independent properties**, or a mathematical equation relating properties to geometry, to predict quasi-static crushing of composite structures?



NASA built, tested (static and dynamically) and analyzed C-channel and Corrugated panels (based on geometry provided originally by Honda R & D) but utilizing a material system (braided T700S/TC275-1 PMC) that we had good understanding on.



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Material Characterization Experiments

- Prior in-house characterization testing was conducted on braided T700S/TC275-1 quasi-isotropic $[0/+60/-60]_s$ composite material
- Results constitute baseline lamina properties

TABLE 1 —BASELINE ROOM-TEMPERATURE LAMINA

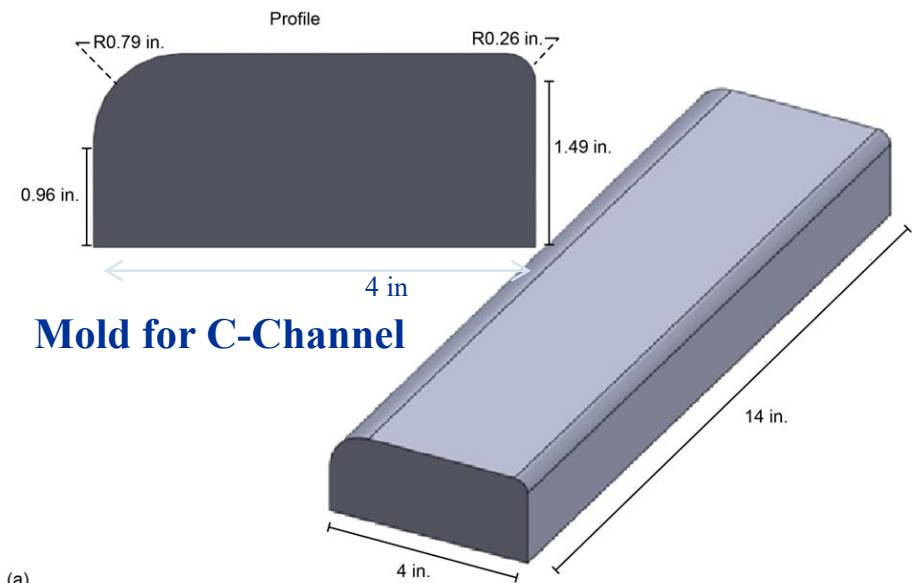
Model parameter	Tension	Compression
Longitudinal Young's modulus, E_{11} , Msi	6.55	6.26
Transverse Young's modulus, E_{22} , Msi	6.34	6.06
Longitudinal Poisson's ratio, ν_{12}	0.24	0.24
Longitudinal shear modulus, G_{12} , Msi	2.38	2.38
Transverse Poisson's ratio, ν_{21}	0.21	0.21
Longitudinal strength, X, ksi	134.9	82.5
Transverse strength, Y, ksi	127.7	61.4
Shear strength, S_L , ksi	34.3	34.3
Transverse fracture toughness, in.*lb/in. ²	3.1	3.1
Axial fracture toughness, in.*lb/in. ²	20	20

Test Standards:

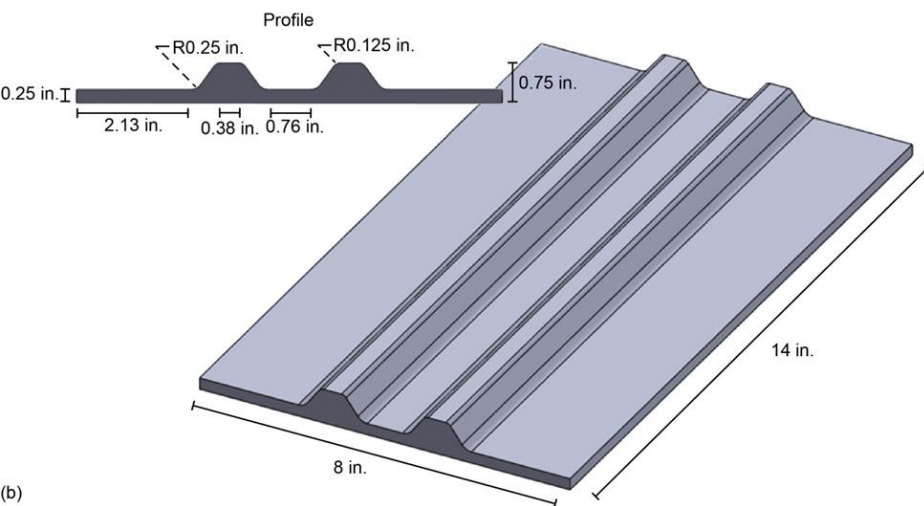
Tensile: ASTM D3039
 Compression: ASTM D6641
 Shear: ASTM D5379
 Fracture
 Toughness: ASTM E833

Geometry and Results of Component Level Experiments

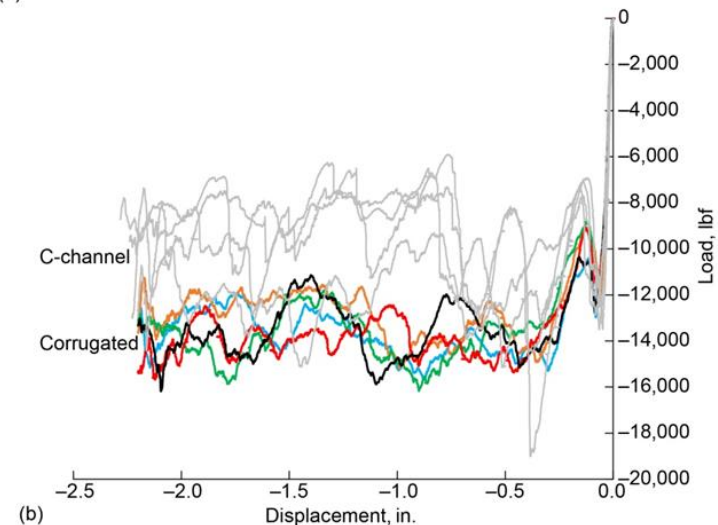
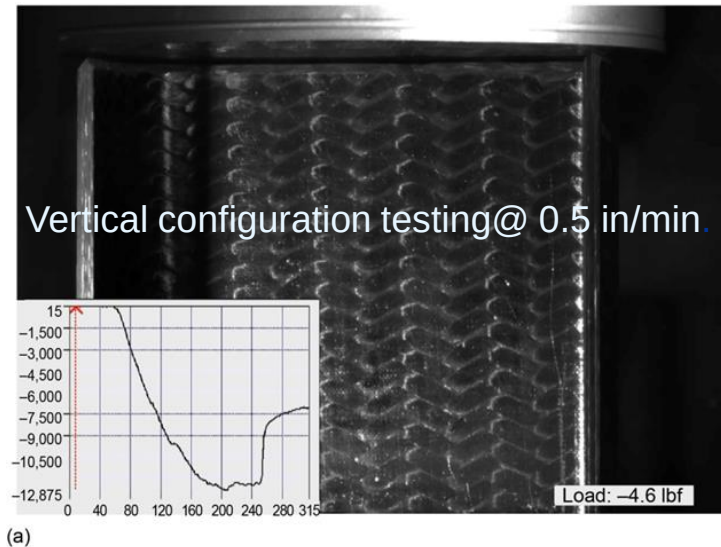
T700S/TC275-1 quasi-isotropic [0/+60/-60]s braided composite system



Mold for C-Channel



Mold for Corrugated Panel



Conducted 5 repetitions for both panel concepts to ascertain the repeatability of the experiment.

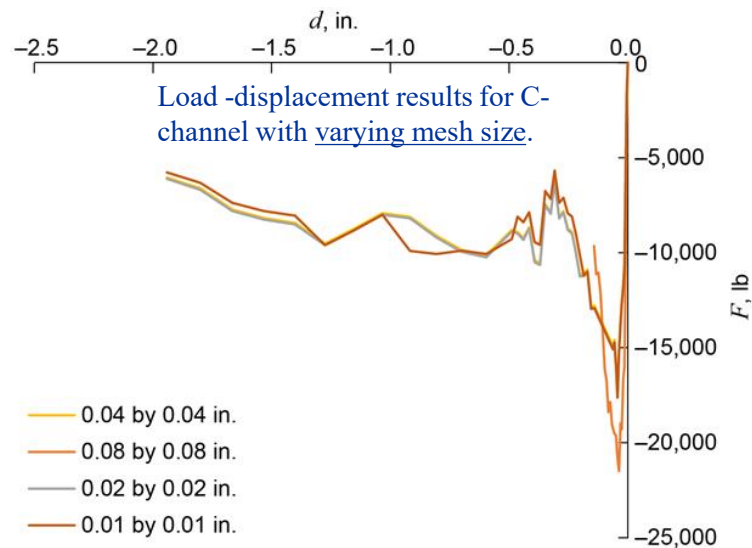


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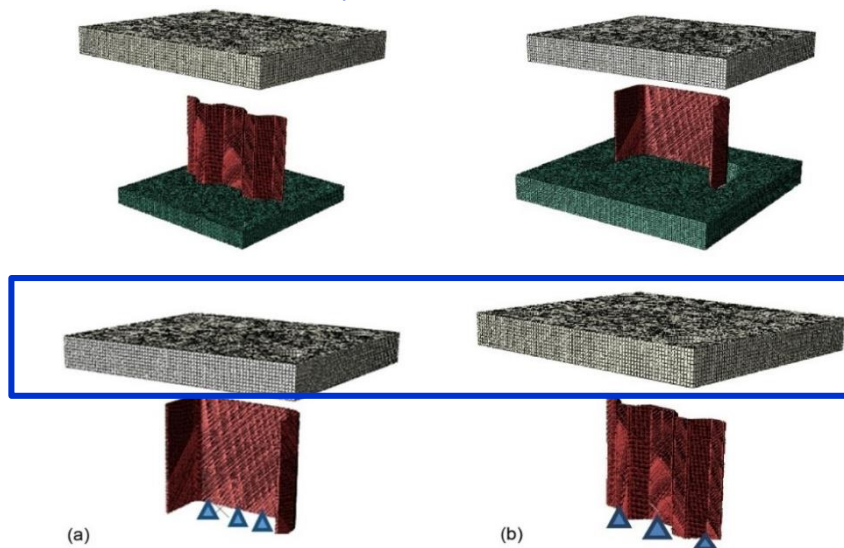
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FEA Model Construction: Important Features

- **Geometry:** C-shaped and corrugated panels with quasi-isotropic $[0/+60/-60]_s$ carbon/epoxy fabric plies.
- **Elements:** Quadrilateral continuum shell elements (SC8R) with homogenized “composite-layup” definition in ABAQUS.
- **Mesh:** A uniform square element (0.04 in. x 0.04 in.) density was used following a mesh convergence study.
- **Boundary Conditions/ Loading:**
 - Replacement of **bottom support plate** with fixed BCs^(a) resulted in 2.3x speed increases without compromising accuracy.
 - Simulated the crush trigger (45° bevel) using a row of reduced thickness elements at the crush front of the specimen.
 - Crushing load was applied to the composite plate through another **solid rigid plate (Rigid Body)**
 - Constant velocity of (900 in/min) utilizing a smooth step definition in ABAQUS.
 - This artificially high velocity had no effect on the analysis results; dynamic effects only become significant beyond a velocity of (3000 in/min).
 - No Mass scaling was used.



LS-Dyna to ABAQUS



Constitutive Model for Reinforced Composites

- The in-plane response of the fabric plies was simulated with the constitutive model for reinforced composites (built-in damage model in ABAQUS).

- Pre-peak linear elastic response governed by elastic properties (longitudinal (E_{11}), transverse (E_{22}), and in-plane shear modulus (G_{12}) under tension and compression).

- Damage initiation criteria:

- Fiber ruptures in tension, fiber buckling in compression, matrix cracking under transverse tension and shearing, and matrix crushing under transverse compression (X , Y , and S represent the ultimate in-plane strength in the longitudinal, transverse, and shear directions).

- Damage propagation:

- Three independent nonnegative in-ply damage parameters, d_f , d_m , and d_s reduce the ply stiffness numerically in the longitudinal, transverse, and shear directions, respectively, until the final failure point (δ_f) is reached

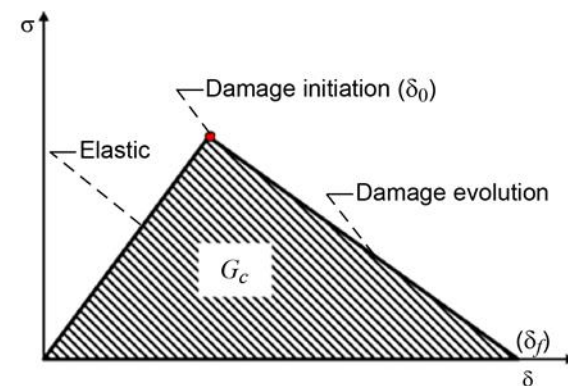
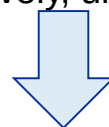
$$\bar{C} = \begin{bmatrix} E_{11}(1-d_f) & (1-d_f)(1-d_m)E_{22}\nu_{21} & 0 \\ (1-d_f)(1-d_m)E_{11}\nu_{12} & E_{22}(1-d_m) & 0 \\ 0 & 0 & 1-(1-d_f)(1-d_m)\nu_{21}\nu_{12}(1-d_s)G \end{bmatrix}$$

$$\left(\frac{\sigma_{11}^{eff}}{X_t}\right)^2 + \left(\frac{\tau_{12}^{eff}}{S_c}\right)^2 = F_t^f$$

$$\left(\frac{\sigma_{11}^{eff}}{X_c}\right)^2 = F_c^f$$

$$\left(\frac{\sigma_{22}^{eff}}{Y_c}\right)^2 + \left(\frac{\tau_{12}^{eff}}{S_c}\right)^2 = F_t^m$$

$$\left(\frac{\sigma_{22}^{eff}}{S_{tr}}\right)^2 + \left(\left(\frac{Y_c^{eff}}{S_{tr}}\right) - 1\right)^2 \frac{\sigma_{22}^{eff}}{Y_c} + \frac{\tau_{12}^{eff}}{S_c} = F_c^m$$



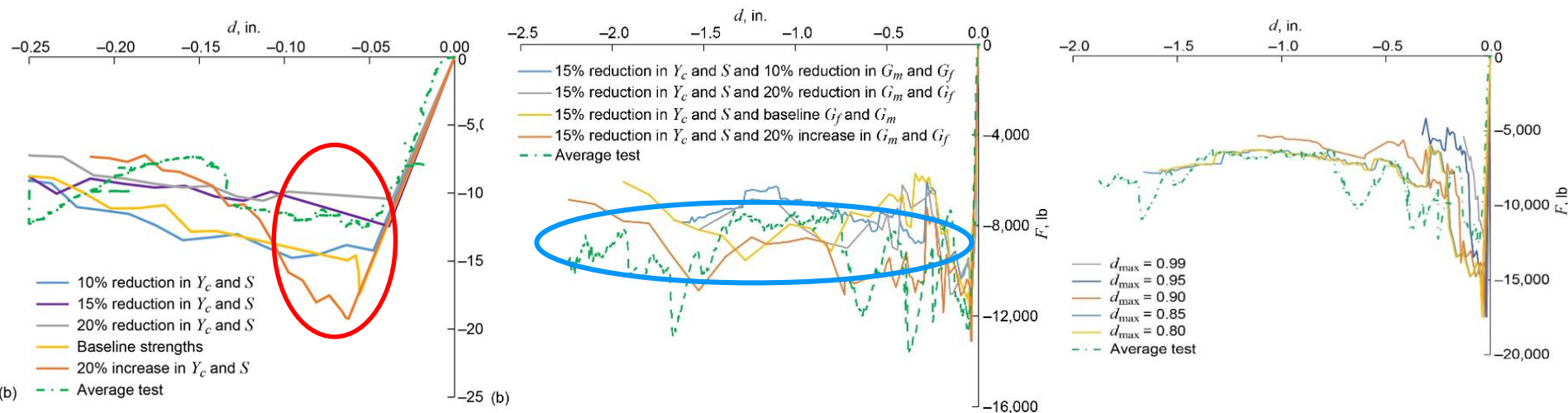


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Parametric Study Provided Insight into ABAQUS Model Parameter Sensitivities

Physical model parameters (strength and fracture toughness) were varied 10 to 20% from baseline values (**Table 1**) to observe the effects on the crushing response. Nonphysical model parameters were also varied to further improve the results.



Increasing/decreasing **lamina failure strength** has a notable impact on the peak crush load with some degree of influence on the post-peak slope.

higher/lower **fracture toughness** values impacts mean post-peak crush load seems to be higher/lower, respectively.

Highly non-linear nature in post-peak crush regions → most of the obtained results lay in the “acceptable” range.

one can lower the limit of **max damage parameter** (d_{max}) to a reasonable degree (~0.85) to avoid the instability caused by the default d_{max} definition in ABAQUS, and still preserve solution accuracy.

Quasi-Static Correlation of Load-Displacement Response of C-channel Concept

The C-channel was used to calibrate material properties and model parameters. This was done by picking the properties that provide the best (*subjective*) fit with the experimental results (Table 2).

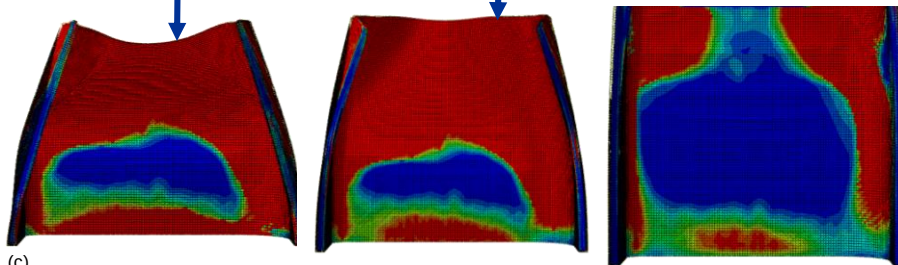
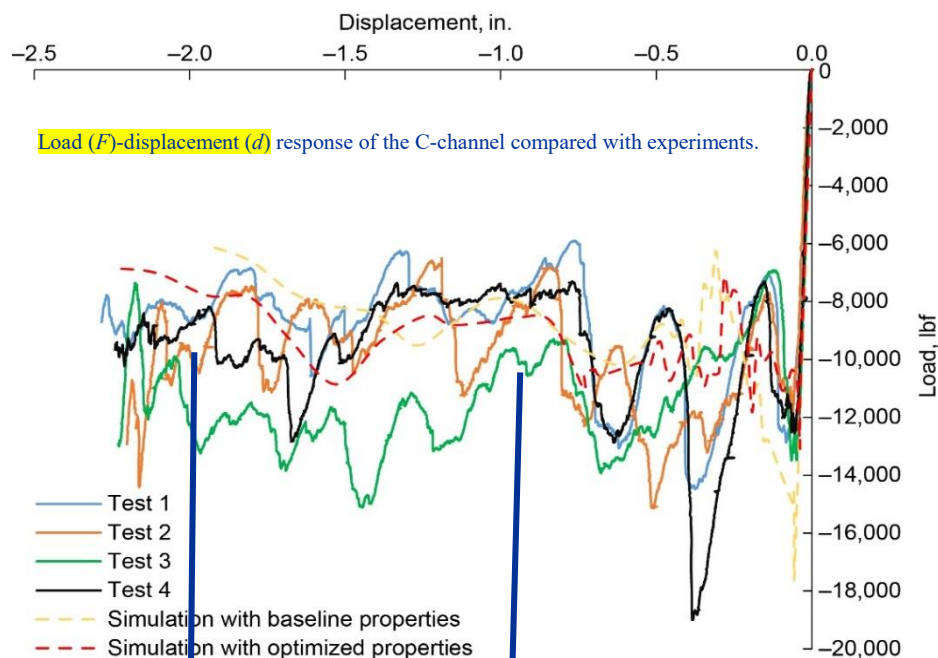


TABLE 2 —OPTIMIZED/IMPROVED MODEL PARAMETERS

Values changed from baseline (after parameter study) shown in **red**

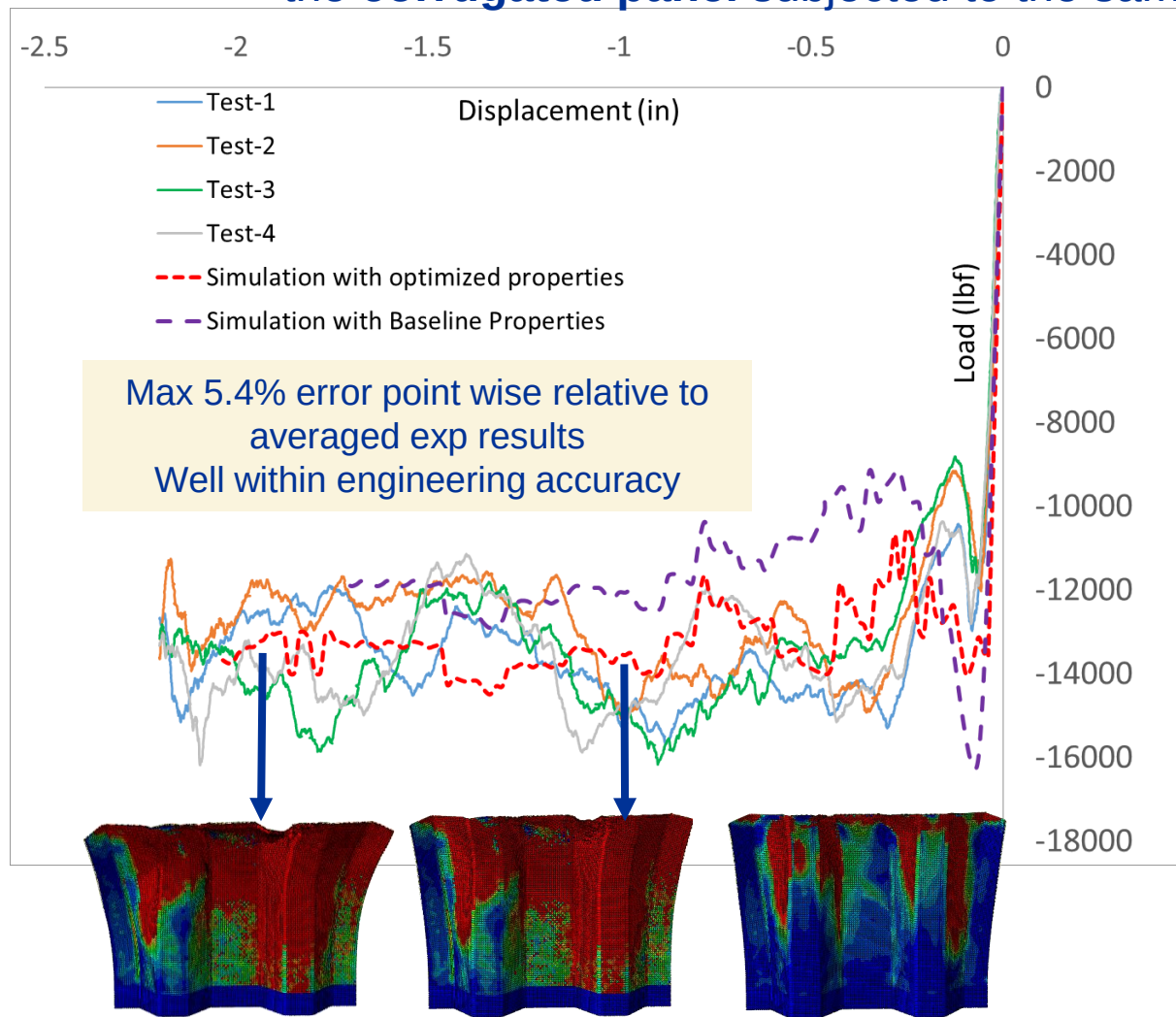
Model parameter	Tension	Compression
Longitudinal Young's modulus, E_{11} , Msi	6.55 (9.5*)	6.26 (9.5*)
Transverse Young's modulus, E_{22} , Msi	6.34 (9.5*)	6.06 (9.5*)
Longitudinal Poisson's ratio, ν_{12}	0.24	0.24
Longitudinal shear modulus, G_{12} , Msi	2.38	2.38
Transverse Poisson's ratio, ν_{21}	0.21	0.21
Longitudinal strength, X, ksi	134.9	82.5
Transverse strength, Y, ksi	127.7	52
Shear strength, S_L , ksi	34.3	27
Transverse fracture toughness, in.*lb/in. ²	3.8	3.8
Axial fracture toughness, in.*lb/in. ²	24	24

(* SHOWS THE VALUE FOR DYNAMIC SIMULATIONS)



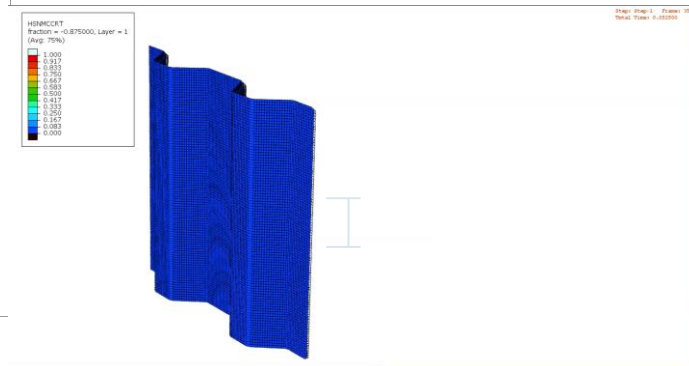
Prediction of *Quasi-static* Corrugated Panel Response

The optimized parameter set (Table 2) **enabled prediction** of the crushing response of the **corrugated panel** subjected to the same loading scenario.



Exact same properties were used in corrugated channel as in the C-channel to reproduce experimental results, making it a pure prediction.

Example videos showing Damage Propagation vs undeformed panel geometry



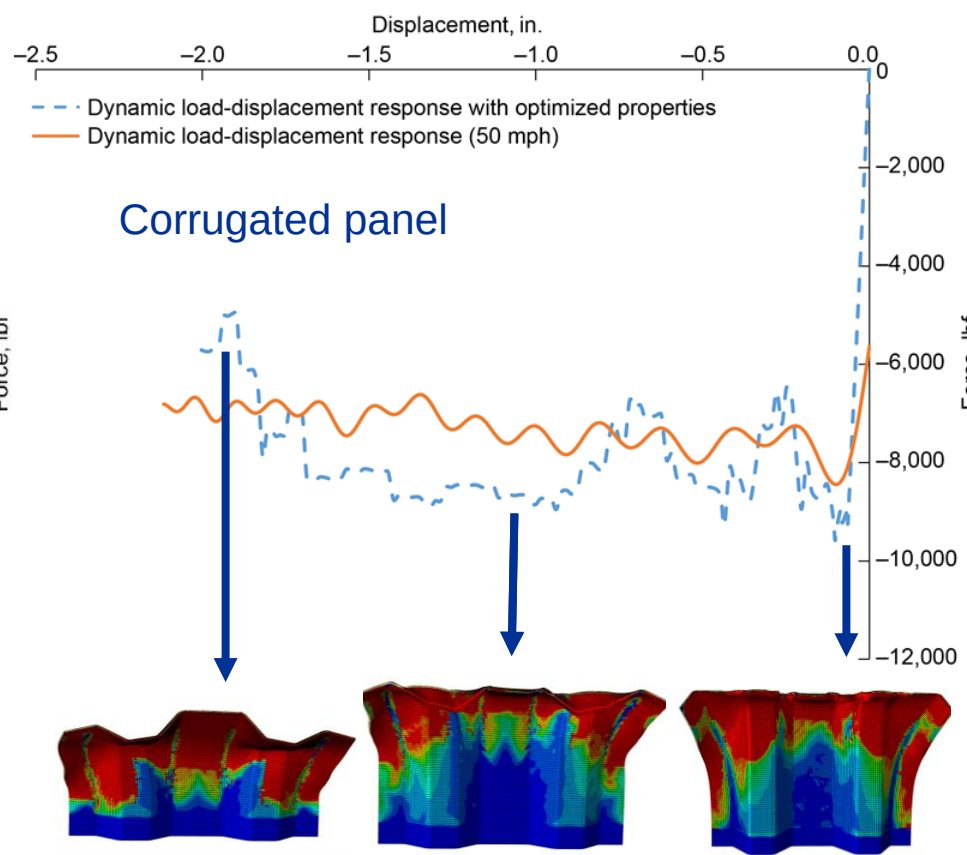
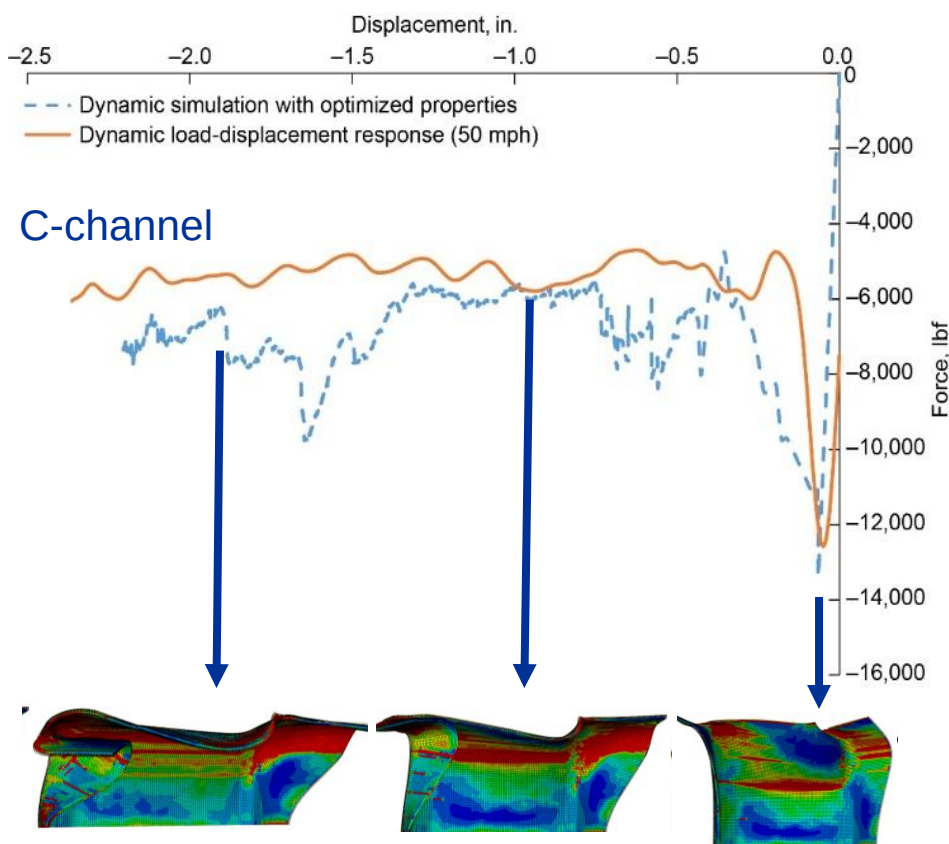


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Dynamic response for Both C-channel and corrugated Panels

- Dynamic response of both plate specimens were “predicted” using the same optimized set of model parameters (Table 2).
- However elastic moduli was adjusted manually to account for known rate dependent (dynamic) effects – (the same dynamic moduli was used for both C-channel and Corrugated panels).





Conclusion and Lessons Learned

- With a short parametric study, one can achieve relatively reliable results with readily available engineering tools in ABAQUS.
- Quasi-static predictive capability of the built-in Hashin progressive damage model in ABAQUS was successfully demonstrated.
 - Initial calibration: C-channel: compile list of “optimized” material properties providing the best “fit” against experimental results.
 - Prediction: Quasi-static response of the corrugated panel.
 - The model’s predictive capability can be further tested on a given 3rd geometry.
- Lessons learned from the parametric study:
 - increase / decrease lamina strength → increase/decrease peak crush load
 - increase / decrease fracture toughness → increase / decrease post-peak slope.
 - one can still preserve solution accuracy and lower the $d_{\max}$ limit to a reasonable degree (~0.85) to avoid solution instability.
- Preliminary Dynamic model capability was also demonstrated on both C-channel and corrugated panels.
 - One major shortcoming: Inherent lack of rate-dependency in the in-built damage model.



Thanks for Your Attention

Questions/Discussion



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