

# **STS-1 FORWARD RCS OXIDIZER TANK SUBSYSTEM STRUCTURAL FAILURE ASSESSMENT**

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**CoSEM CDT  
University of Bristol  
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# **STS-1 Forward RCS Oxidizer Tank Subsystem Structural Failure Assessment**

- **Study rationale**
- **Landing and post-flight inspection**
- **Launch and ignition overpressure (IOP)**
- **Orbiter reaction control system (RCS), forward RCS module, and oxidizer tank subsystem**
- **Oxidizer tank support strut loads**
- **Closed-form structural and failure analyses**
- **Nonlinear finite element analyses**
- **Concluding remarks**

# Why Study This Problem? - Motivation

- Known *of* this incident, but not really *about* it...
- Only passing references found
- Sparse technical details available
- My attempt to remedy this gap



## STS-1 SRB Ignition Overpressure (IOP)

### Problem

- Solid rocket booster (SRB) ignition overpressure (IOP) measured at the vehicle exceeded the 3-sigma liftoff design environment
  - Accelerations measured on the wing, body flap, vertical tail, and crew cabin exceeded predictions during the liftoff transient
  - **Support struts for the orbiter's reaction control system (RCS) oxidizer tank buckled**
- Post-flight analysis revealed that SRB IOP was much more violent than predicted



NASA Virtual Project Management Challenge • #askVPMC

4

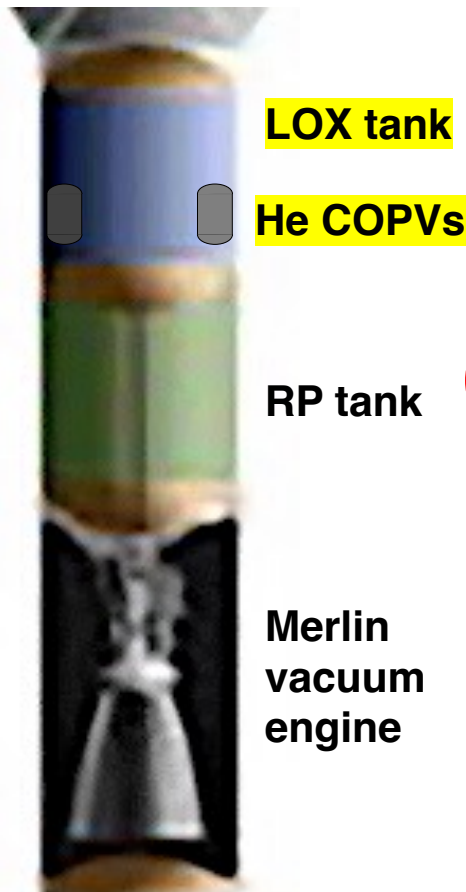
# Why Study This Problem? - Still Relevant Today

- ISS resupply mission CRS-7, July 2015
- 19th launch of SpaceX Falcon 9
- Stage 2 LOX tank ruptured on ascent
- He COPV *strut failure credible root cause*



Credit: NASA/KSC

## Why Study This Problem? - Still Relevant (2)



[https://www.spacex.com/media/falcon\\_users\\_guide\\_042020.pdf](https://www.spacex.com/media/falcon_users_guide_042020.pdf)



- Falcon 9 Stage 2 (LOX/RP prop)  
- 3.7m diam. x 14.8m length
- LOX tank with submerged He COPVs
- COPVs supported with strut network



# Spoiler Alert - It Worked!



## Landing at Edwards AFB - 14 April 1981



Credit: NASA/JSC

K.C.Wu 7

# The Crew, Young and Crippen



Credit: NASA/JSC

# The Crew, Young and Crippen



Credit: NASA/JSC

# Orbiter Post-Flight Inspection

| FLIGHT TEST PROBLEM REPORT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |  | NO. 58                            |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|-----------------------------------|
| Statement of problem:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |  | scg 8/3/81                        |
| Forward RCS oxidizer tank aft Z strut found deformed.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |  |                                   |
| Discussion:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |  |                                   |
| <p>The forward RCS oxidizer aft Z strut failed in Euler buckling due to the lift-off dynamic response from the SRB overpressure. The forward and aft Z axis tank struts on both the fuel and the oxidizer tanks were replaced with struts reinforced by plies of boron/epoxy. The rod end diameter of the fuel tank struts was increased by 1/16 in. to be the same as the diameter of the oxidizer struts.</p> <p>The base heat shield left and right struts were reinforced and replaced. All other large mass support systems were reassessed for positive margins.</p> |  |                                   |
| Required date for resolution:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |  | CLOSED 7/22/81 <i>David Cohen</i> |
| Personnel assigned: E. W. Sanders/ES2 X-6156, R. J. Ward/WA3 X-4323                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |  |                                   |
| Action progress:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |  |                                   |
| (blank)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |  |                                   |
| Effect on subsequent missions:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |  |                                   |
| None                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |  |                                   |
| Conclusions:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |  |                                   |
| Z axis accelerations exceeded design limits due to SRB overpressure which resulted in deformation of the forward RCS oxidizer tank aft Z strut.                                                                                                                                                                                                                                                                                                                                                                                                                            |  |                                   |
| Corrective action:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |  |                                   |
| Forward RCS struts were modified and replaced. Base heat shield left and right struts were reinforced and replaced. All large mass structures were analyzed and found to have positive margins of safety.                                                                                                                                                                                                                                                                                                                                                                  |  |                                   |

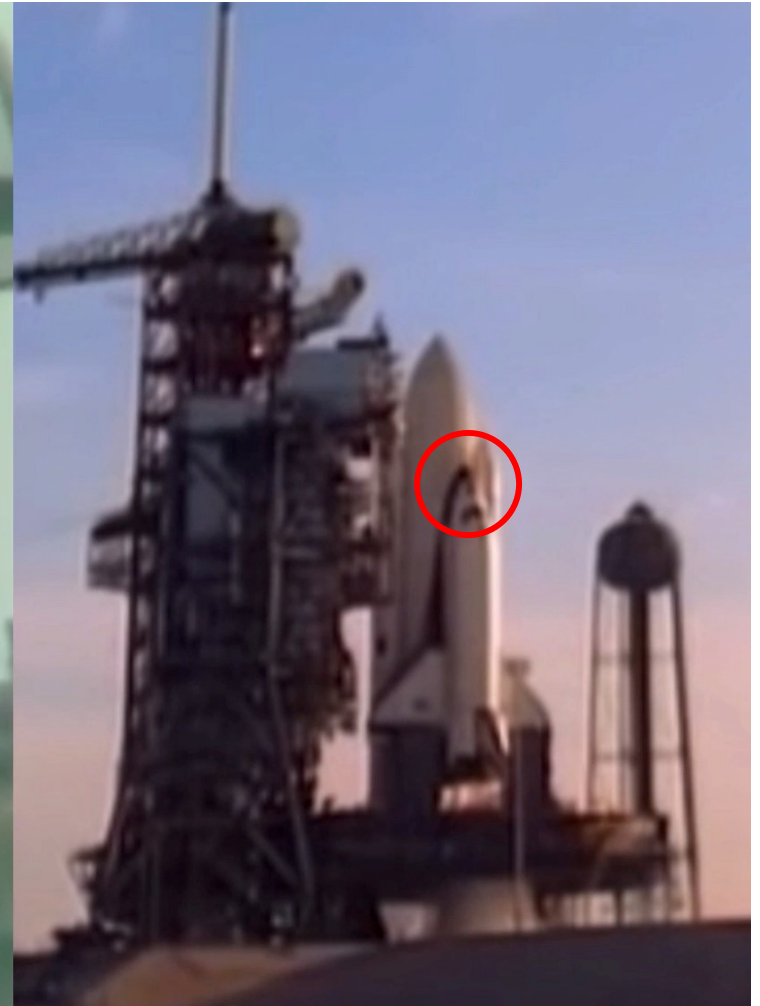
## STS-1 Orbiter Final Mission Report, JSC-17378, Aug. 1981

### In-Flight Anomaly STS-1-V-58 (IFA V-58)

***“Forward RCS oxidizer tank aft Z strut found deformed.”***

***“The ... strut failed in Euler buckling due the lift-off dynamic response from the SRB overpressure.”***

## April 12, 1981 - Liftoff!

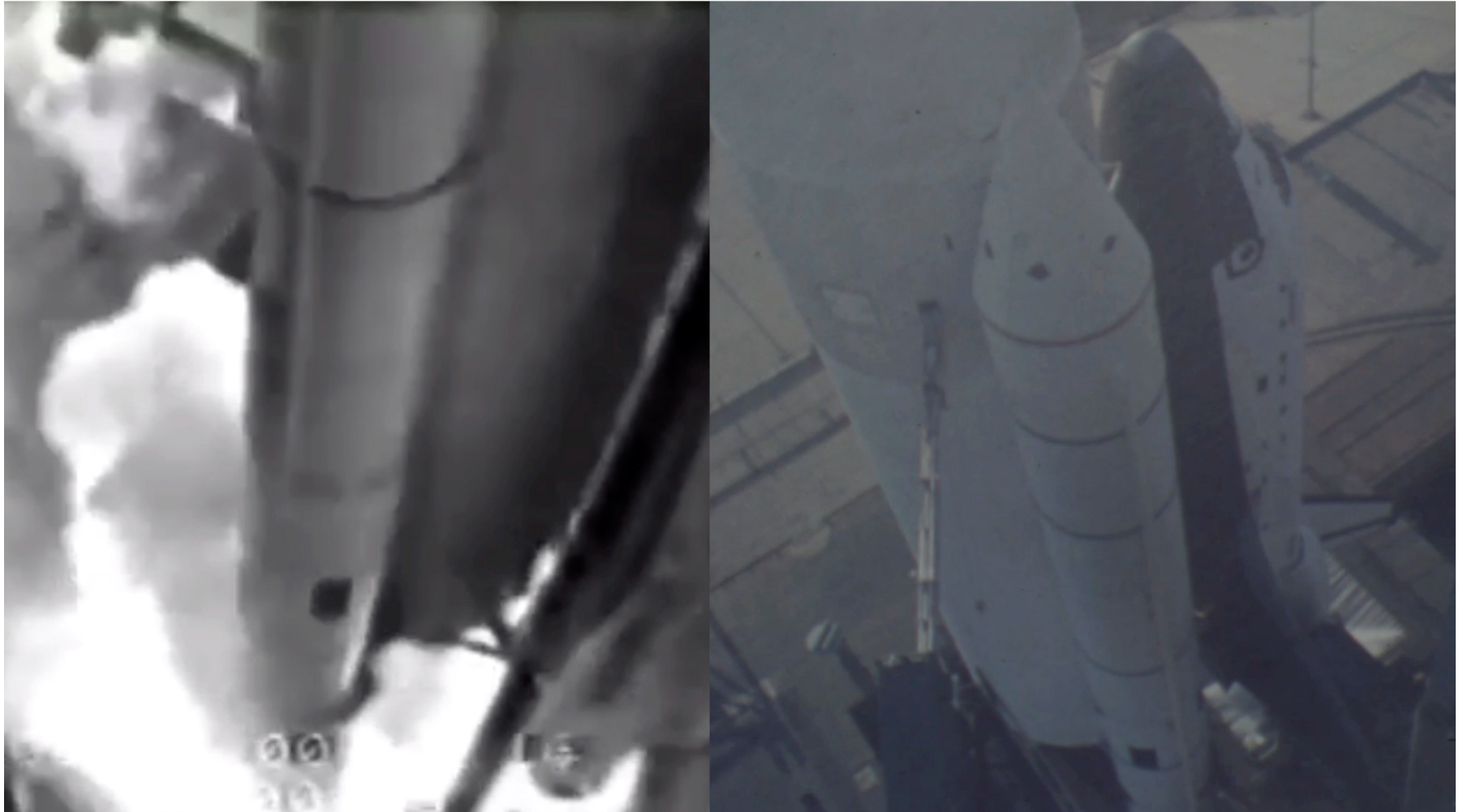


**LC-39A Perimeter Camera Views**

Credit: NASA/JSC



## April 12, 1981 - Liftoff! (2)



**Fixed Service Structure Camera Views**

Credit: NASA/JSC



## Ignition Overpressure (IOP)

- **At solid rocket booster (SRB) ignition, a strong transient IOP wave swept up the Shuttle stack**
- SRB IOP environment was predicted pre-flight with analyses and scale-model testing
- Orbiter frequency response to IOP was greater than pre-flight predictions, exciting vehicle bending
- Peak Z (normal) accelerations of  $-2\text{ g}$  to  $+3.5\text{ g}$  were reported in Orbiter cockpit
- IOP also caused aft heat shield and aerosurface acoustic loading at or near design limits

# Ignition Overpressure (IOP)

## NASA TECHNICAL MEMORANDUM

NASA TM-82458

(NASA-TM-82458) PROPULSION SYSTEM IGNITION  
OVERPRESSURE FOR THE SPACE SHUTTLE (NASA)  
70 p MC A04/AF A01 CSCL 20H

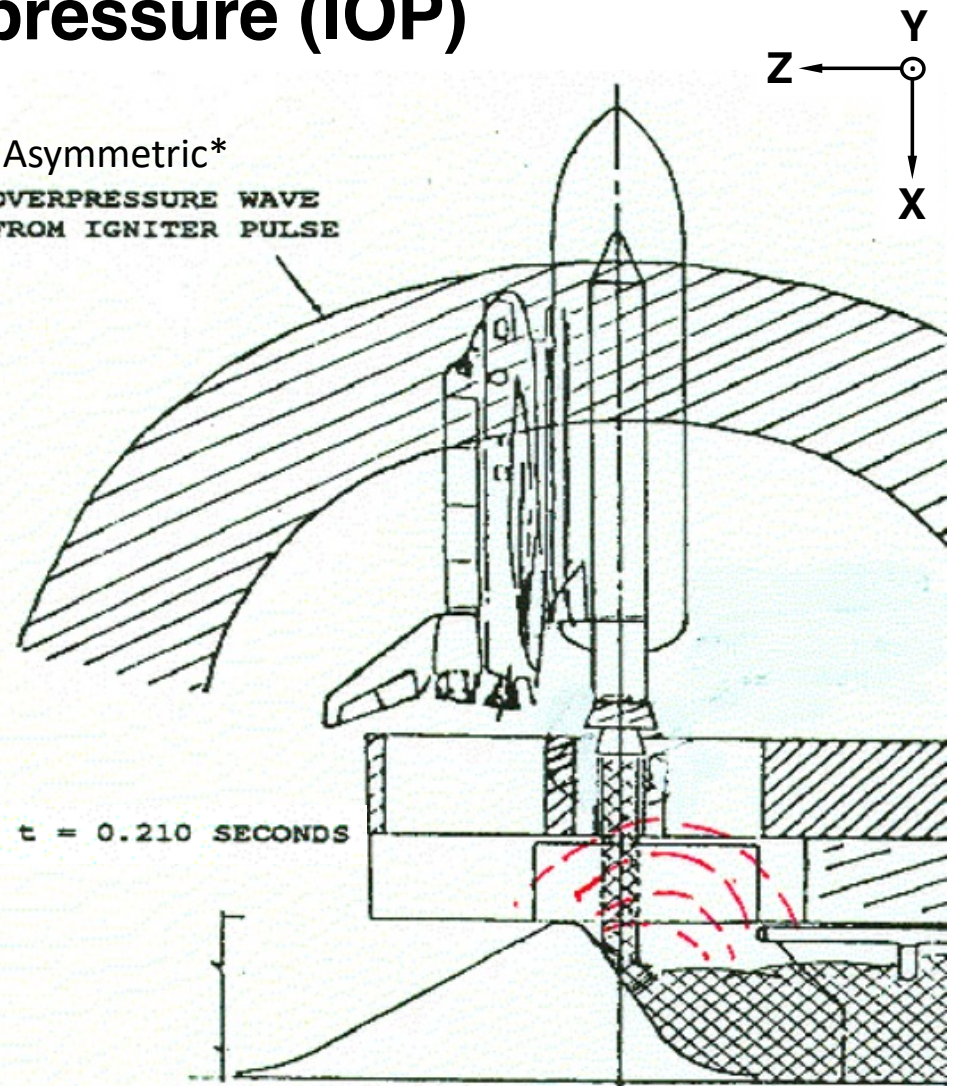
### PROPULSION SYSTEM IGNITION OVERPRESSURE FOR THE SPACE SHUTTLE

By R. S. Ryan, J. H. Jones, S. H. Guest, H. G. Struck,  
M. H. Rheinfurth, and V. S. Verderaine

December 1981

\*Asymmetric\*

OVERPRESSURE WAVE  
FROM IGNITER PULSE



## Ignition Overpressure (2)

- At solid rocket booster (SRB) ignition, a strong transient IOP wave swept up the Shuttle stack
- **SRB IOP environment was predicted pre-flight with analyses and scale-model testing**
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- IOP also caused aft heat shield and aerosurface acoustic loading at or near design limits

## 6.4-Percent Scale Model Testing, pre-STS-1



Credit: NASA/MSFC

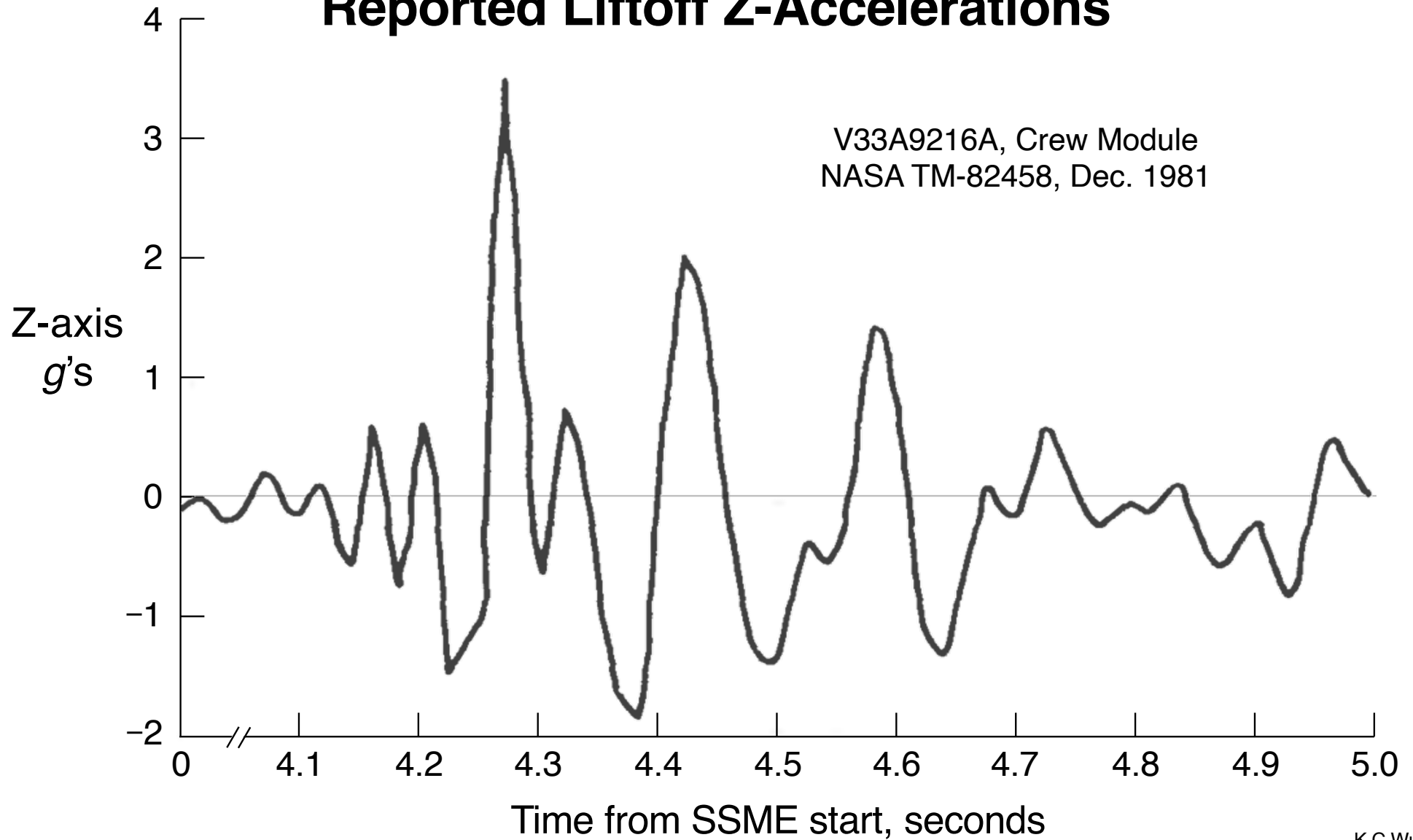


Credit: NASA/David Piatak

## Ignition Overpressure (3)

- At solid rocket booster (SRB) ignition, a strong transient IOP wave swept up the Shuttle stack
- SRB IOP environment was predicted pre-flight with analyses and scale-model testing
- **Orbiter frequency response to IOP was greater than pre-flight predictions, exciting vehicle bending**
- **Peak Z (normal) accelerations of  $-2\text{ g}$  to  $+3.5\text{ g}$  were reported in Orbiter cockpit**
- IOP also caused aft heat shield and aerosurface acoustic loading at or near design limits

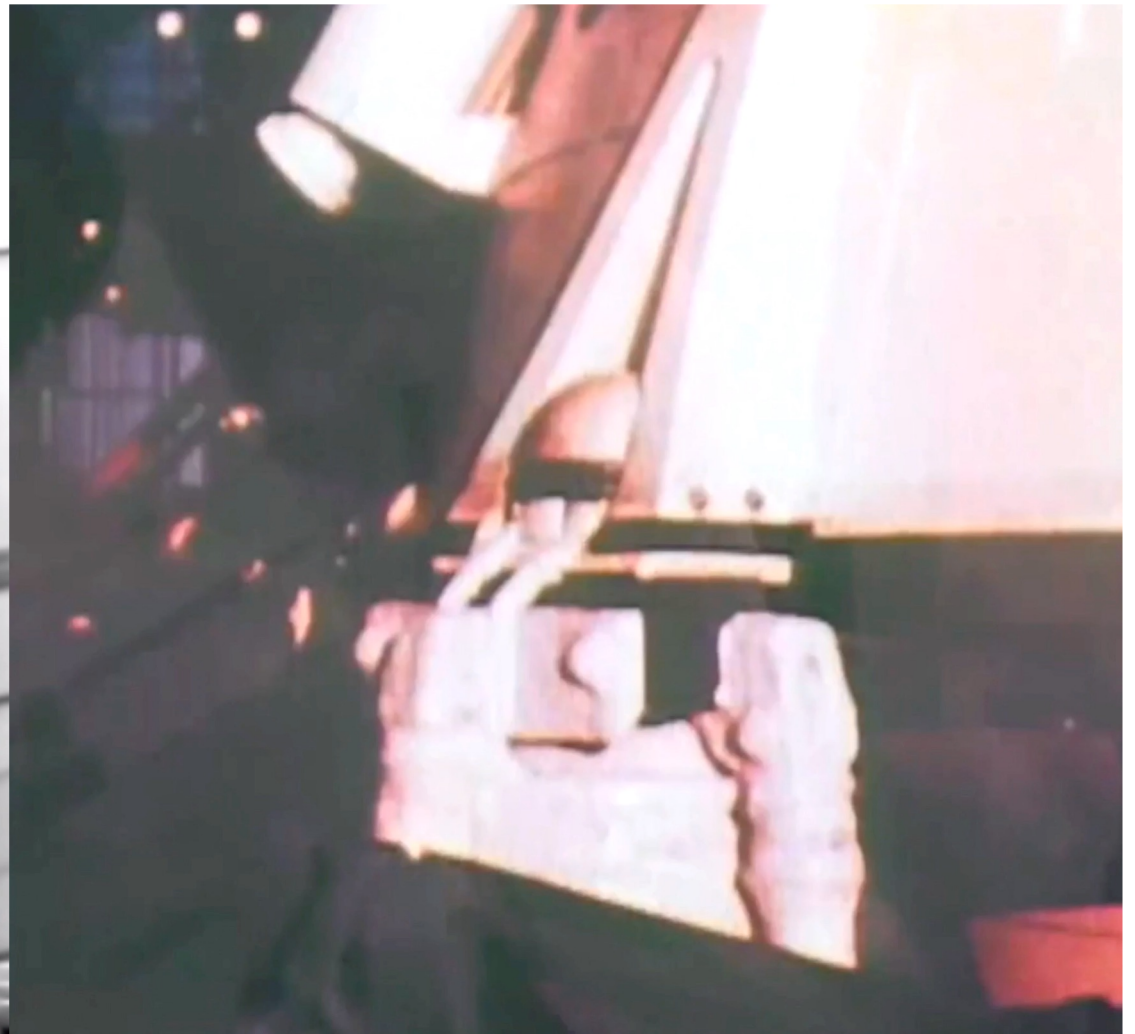
# Reported Liftoff Z-Accelerations



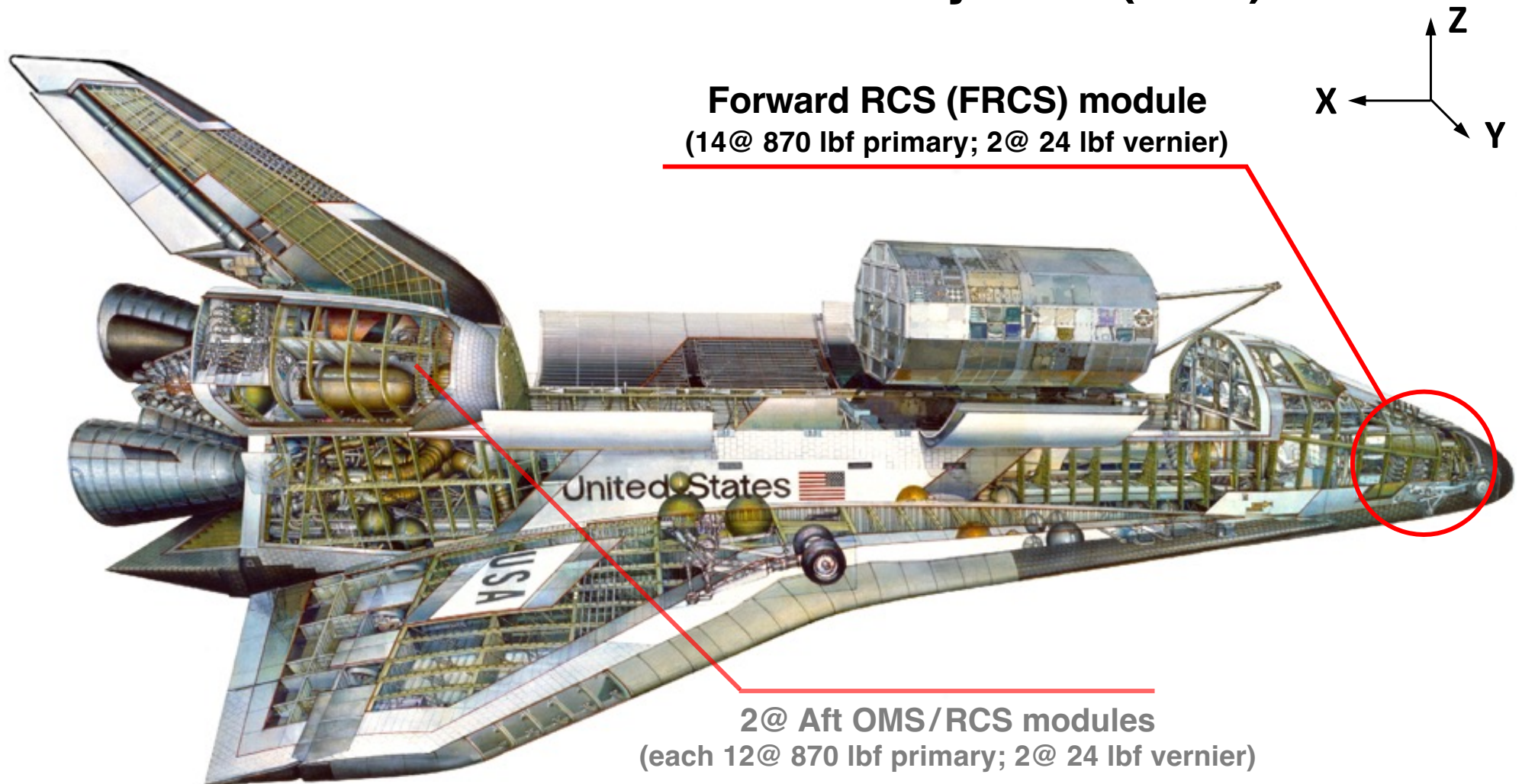
## Ignition Overpressure (4)

- At solid rocket booster (SRB) ignition, a strong transient IOP wave swept up the Shuttle stack
- SRB IOP environment was predicted pre-flight with analyses and scale-model testing
- Orbiter frequency response to IOP was greater than pre-flight predictions, exciting vehicle bending
- Peak Z (normal) accelerations of  $-2\text{ g}$  to  $+3.5\text{ g}$  were reported in Orbiter cockpit
- **IOP also caused aft heat shield and aerosurface acoustic loading at or near design limits**

## Orbiter Aerosurface Response to IOP



# Orbiter Reaction Control System (RCS)

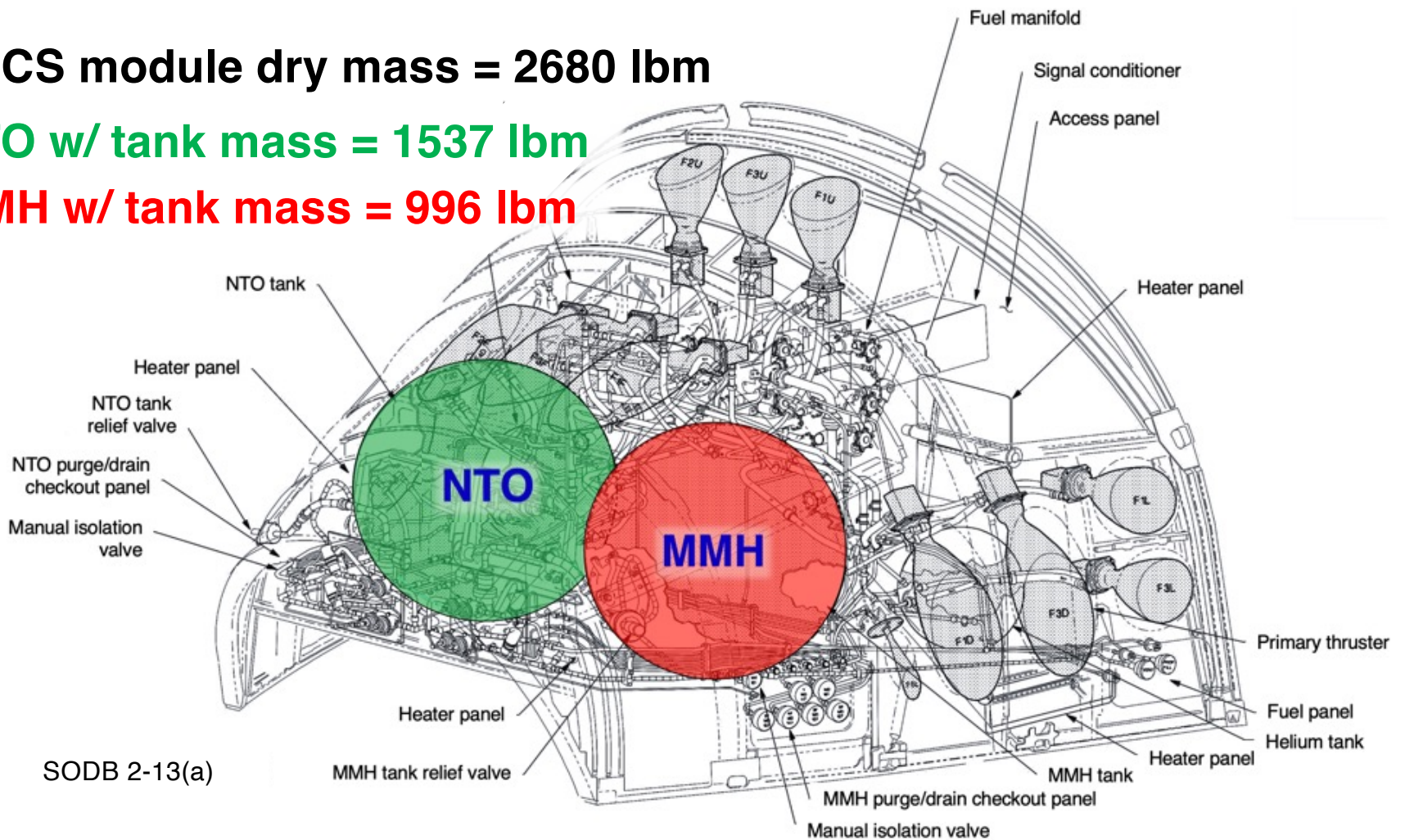


# FRCS Module and Propellant Tanks

**FRCS module dry mass = 2680 lbm**

**NTO w/ tank mass = 1537 lbm**

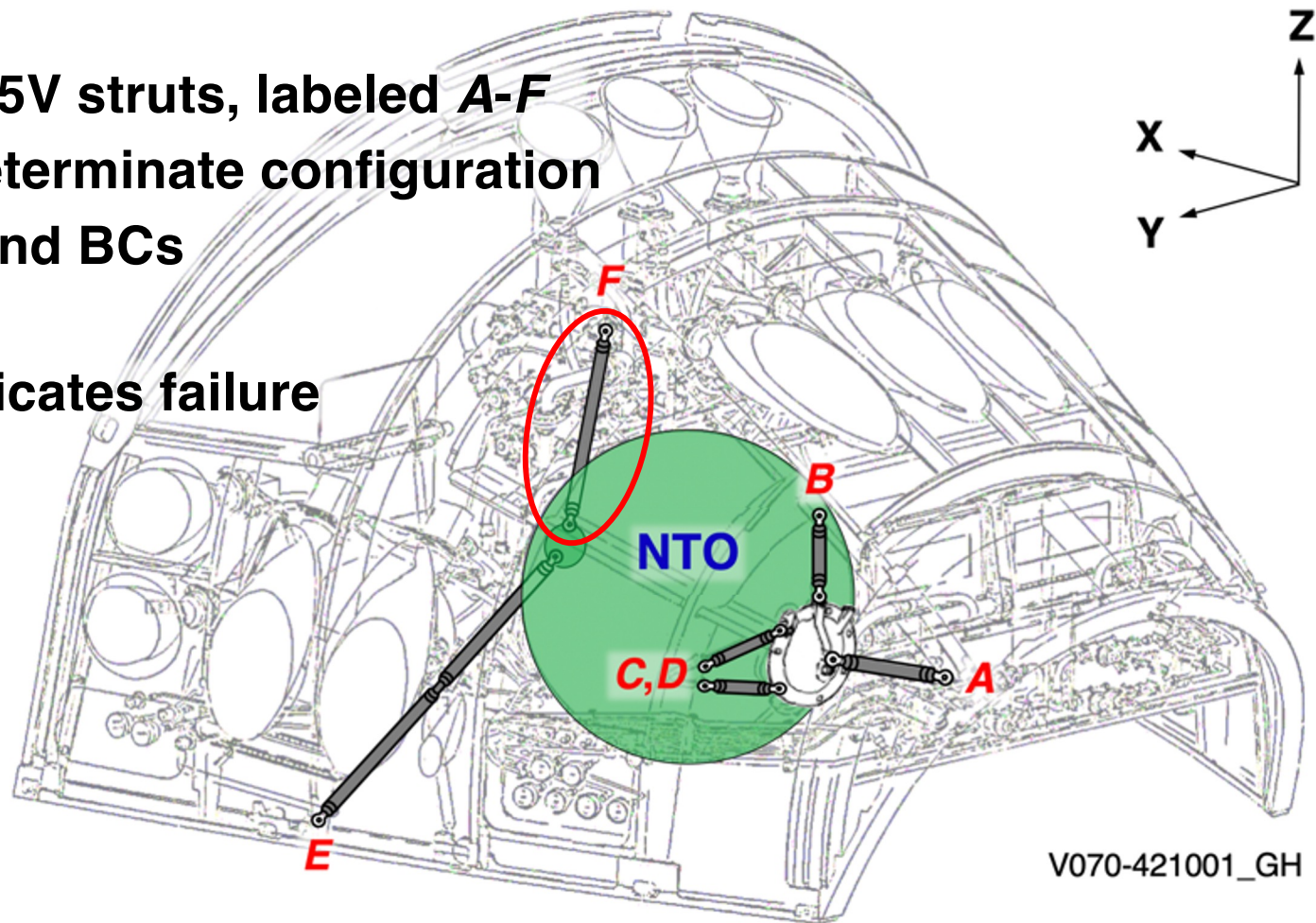
**MMH w/ tank mass = 996 lbm**



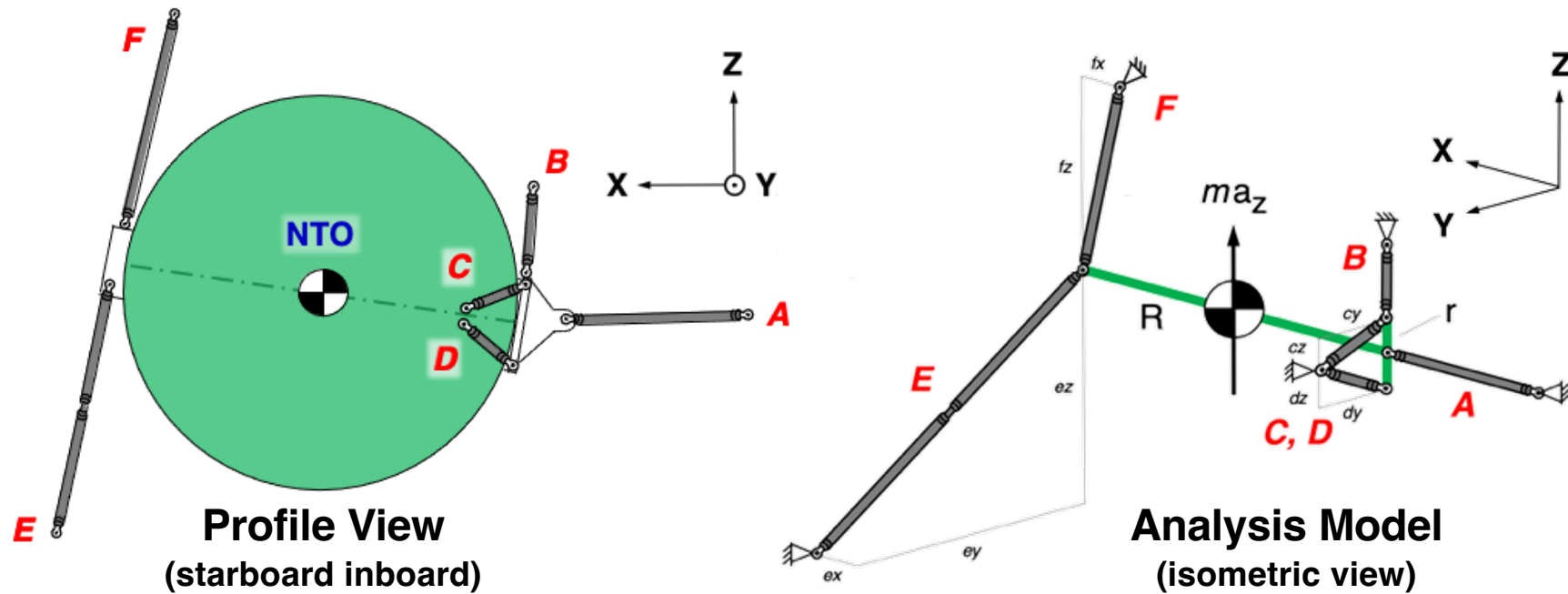
# FRCS Oxidizer Tank Subsystem

Six Ti-3Al-2.5V struts, labeled **A-F**  
Statically determinate configuration  
All pinned-end BCs

IFA V-58 indicates failure  
of **Strut F**



# Oxidizer Tank Subsystem Model



- Rigid tank and FRCS module structures
- Statically determinate  $\Rightarrow$  Solve equilibrium for individual strut forces  $P_i$ ,  $i = A, \dots F$
- Calculate  $P_F = -ma_z / (2 f_z)$ ,  $P_B = -ma_z / 2$

# IFA V-58 Report

| FLIGHT TEST PROBLEM REPORT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |  | NO. 58                            |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|-----------------------------------|
| Statement of problem:<br>Forward RCS oxidizer tank aft Z strut found deformed.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |  | scg 8/3/81                        |
| <p>Discussion:</p> <p>The forward RCS oxidizer aft Z strut failed in Euler buckling due to the lift-off dynamic response from the SRB overpressure. The forward and aft Z axis tank struts on both the fuel and the oxidizer tanks were replaced with struts reinforced by plies of boron/epoxy. The rod end diameter of the fuel tank struts was increased by 1/16 in. to be the same as the diameter of the oxidizer struts.</p> <p>The base heat shield left and right struts were reinforced and replaced. All other large mass support systems were reassessed for positive margins.</p> |  |                                   |
| Required date for resolution:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |  | CLOSED 7/22/81 <i>David Cohen</i> |
| Personnel assigned: E. W. Sanders/ES2 X-6156, R. J. Ward/WA3 X-4323                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |  |                                   |
| Action progress:<br>(blank)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |  |                                   |
| Effect on subsequent missions:<br>None                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |  |                                   |
| <p>Conclusions:</p> <p>Z axis accelerations exceeded design limits due to SRB overpressure which resulted in deformation of the forward RCS oxidizer tank aft Z strut.</p>                                                                                                                                                                                                                                                                                                                                                                                                                    |  |                                   |
| <p>Corrective action:</p> <p>Forward RCS struts were modified and replaced. Base heat shield left and right struts were reinforced and replaced. All large mass structures were analyzed and found to have positive margins of safety.</p>                                                                                                                                                                                                                                                                                                                                                    |  |                                   |

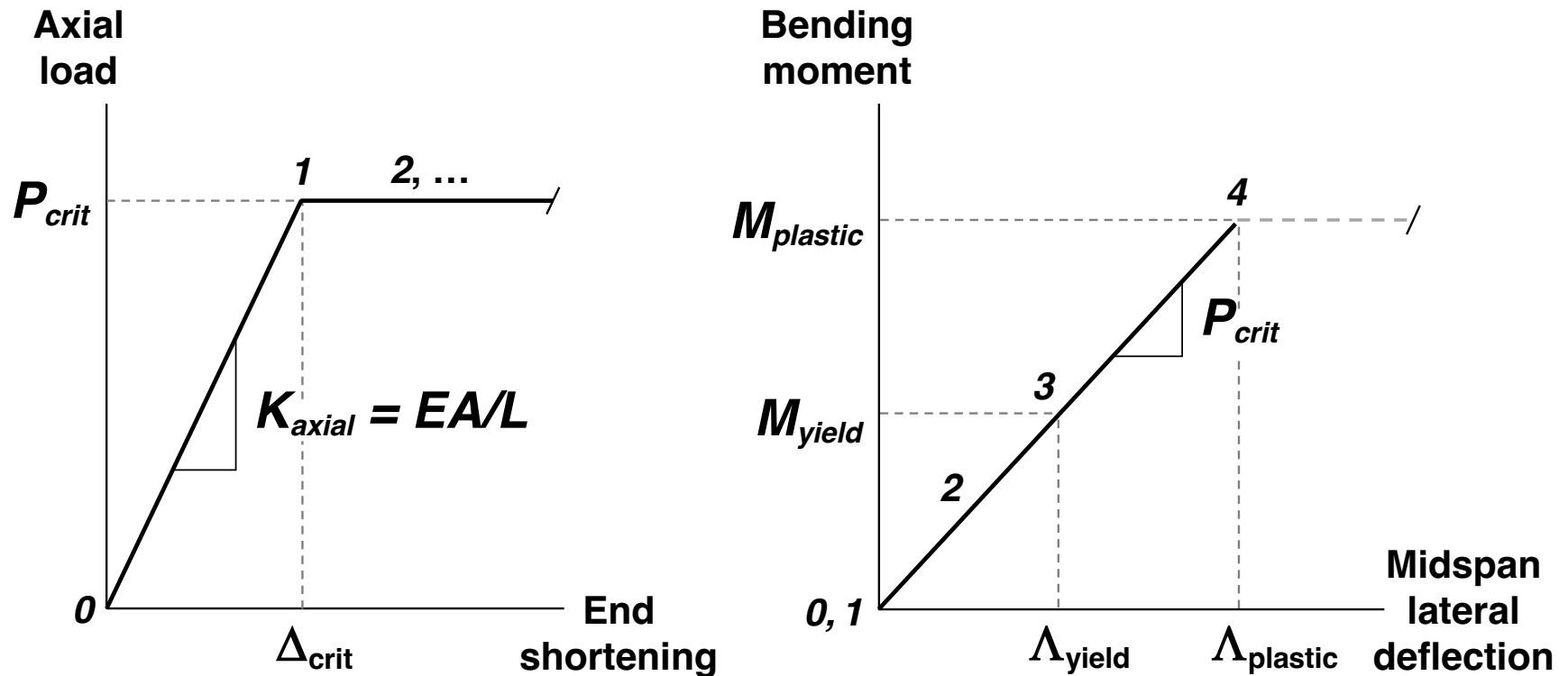
STS-1 Orbiter Final Mission Report, JSC-17378, Aug. 1981

In-Flight Anomaly STS-1-V-58 (IFA V-58)

*“Forward RCS oxidizer tank aft Z strut found deformed.”*

***“The ... strut failed in Euler buckling due the lift-off dynamic response from the SRB overpressure.”***

# Idealized Strut Structural Response

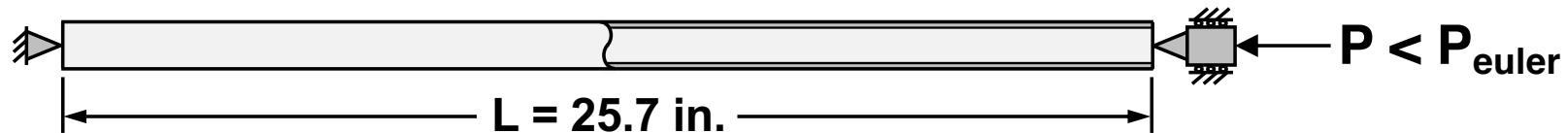


**Ti-3Al-2.5V material assumed elastic-perfectly plastic**

$$E = 15.4 \text{ Mlb/in}^2, \sigma_{cy} = -108 \text{ klb/in}^2$$

# NTO Strut $F$ Structural Analysis

- Simplified analysis model developed
  - Actual dimensions;  $D = 1.25$  in.,  $T = 0.025$  in.
  - No geometric imperfections, pinned ends
  - Elastic-perfectly plastic material;  $E$ ,  $\sigma_{cy}$

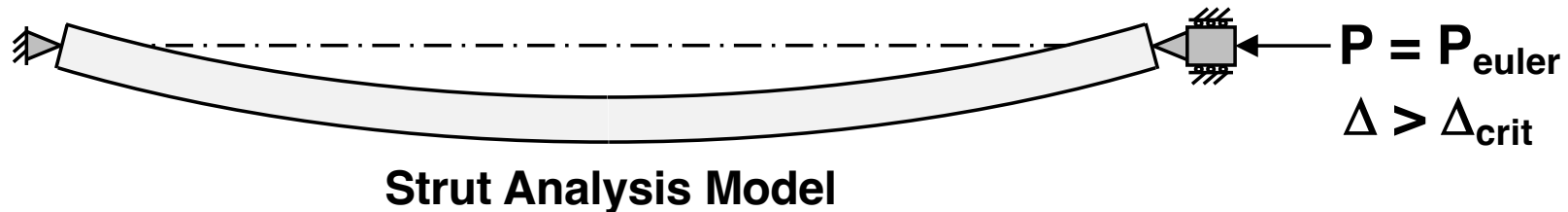


Strut Analysis Model

- Calculate Euler buckling load for slender strut  
 $P_{euler} = -4142$  lbf
- Static  $a_z = +5.24 g$  required for buckling
- Euler buckling is *elastic* failure  
 $\Rightarrow$  No lateral deflection for  $P < P_{euler}$ ;  $\Lambda = 0$

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- Static  $a_z = +5.24 g$  required for buckling
- Euler buckling is *elastic* failure  
 $\Rightarrow$  Lateral deflection  $\Delta > 0$  for  $P = P_{euler}$ ,  $\Delta > \Delta_{crit}$

# IFA V-58 Report (2)

| FLIGHT TEST PROBLEM REPORT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |  | NO. 58            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|-------------------|
| <b>Statement of problem:</b><br>Forward RCS oxidizer tank aft Z strut found deformed.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |  | <i>scg 5/3/81</i> |
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| <b>Action progress:</b><br>(blank)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |  |                   |
| <b>Effect on subsequent missions:</b><br>None                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |  |                   |
| <b>Conclusions:</b><br>Z axis accelerations exceeded design limits due to SRB overpressure which resulted in deformation of the forward RCS oxidizer tank aft Z strut.                                                                                                                                                                                                                                                                                                                                                                                                                           |  |                   |
| <b>Corrective action:</b><br>Forward RCS struts were modified and replaced. Base heat shield left and right struts were reinforced and replaced. All large mass structures were analyzed and found to have positive margins of safety.                                                                                                                                                                                                                                                                                                                                                           |  |                   |

STS-1 Orbiter Final Mission Report, JSC-17378, Aug. 1981

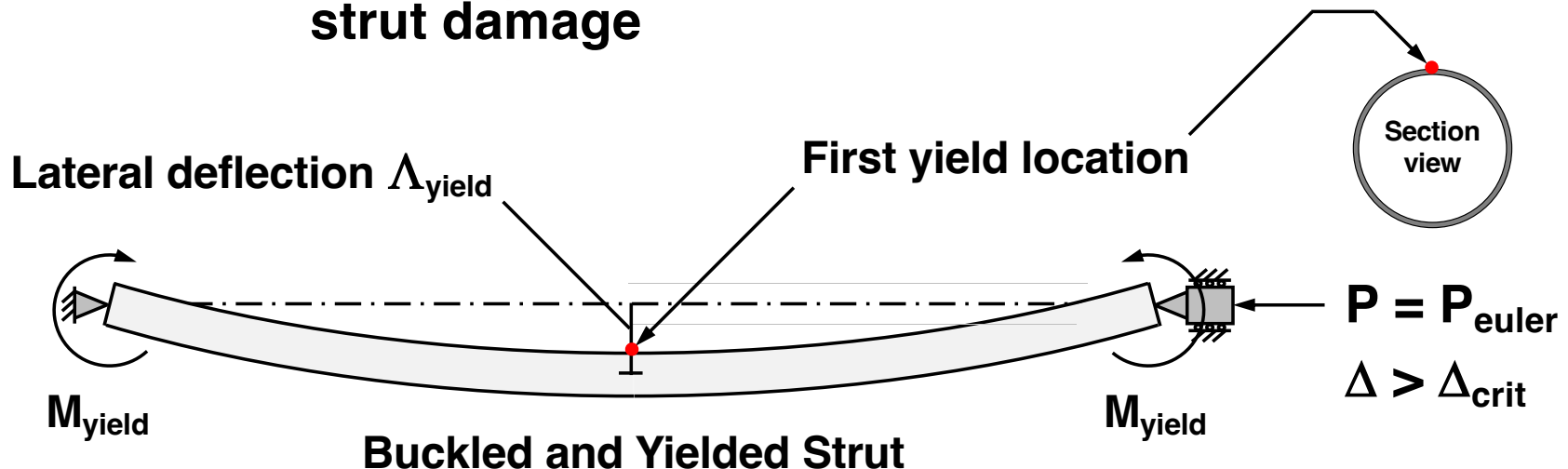
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**“Forward RCS oxidizer tank aft Z strut found deformed.”**

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## NTO Strut $F$ Structural Analysis (2)

- Strut  $F$  deformation noted post-flight  
=> Material yield in deep postbuckling
- Calculate bending moment for **first yield** at strut mid-span,  $M_{\text{yield}} = 1870$  in-lbf
- **Lower-bound estimate** for observed strut damage



## NTO Strut $F$ Structural Analysis (3)

- Strut  $F$  deformation noted post-flight  
=> Material yield in deep postbuckling
- Calculate bending moment for first yield at strut mid-span,  $M_{\text{yield}} = 1870 \text{ in-lbf}$
- Compute strain energies required for...
  - Euler buckling,  $U_{\text{buck}} = 143 \text{ in-lbf}$
  - Bending to first yield,  $U_{\text{bend}} = 81 \text{ in-lbf}$
- Estimate *lower bound* dynamic amplification factor  
 $(U_{\text{buck}} + U_{\text{bend}})/U_{\text{buck}} = \text{DAF} = 1.57$
- Static pseudo-load to buckle and yield Strut  $F$   
$$P_{\text{equiv}} = -4142 \text{ lbf} \times 1.57$$
$$= -6503 \text{ lbf (minimum)}$$

## Additional Strut Failure Analyses

- Calculate force in NTO Strut *B*
  - $P_B = -1537 \text{ lbm} \times 5.24 \text{ g}/2 \times 1.57$   
 $= -6322 \text{ lbf} > P_{\text{johnson}} (-11,757 \text{ lbf})$
- Estimate DAF = 1.86 to fail Strut *B*  
 $\Rightarrow$  **Possible NTO Strut *B* failure**
- Now consider MMH Strut *F*
  - $P_F = -996 \text{ lbm} \times 5.24 \text{ g}/(2 \text{ fz}) \times 1.57$   
 $= -4213 \text{ lbf} < P_{\text{euler}} (-4142 \text{ lbf})$   
 $\Rightarrow$  *Probable* MMH Strut *F* buckling
- However, no corroborating evidence of these failures observed on flight hardware
- MMH Strut *B* failure unlikely (DAF = 2.87)

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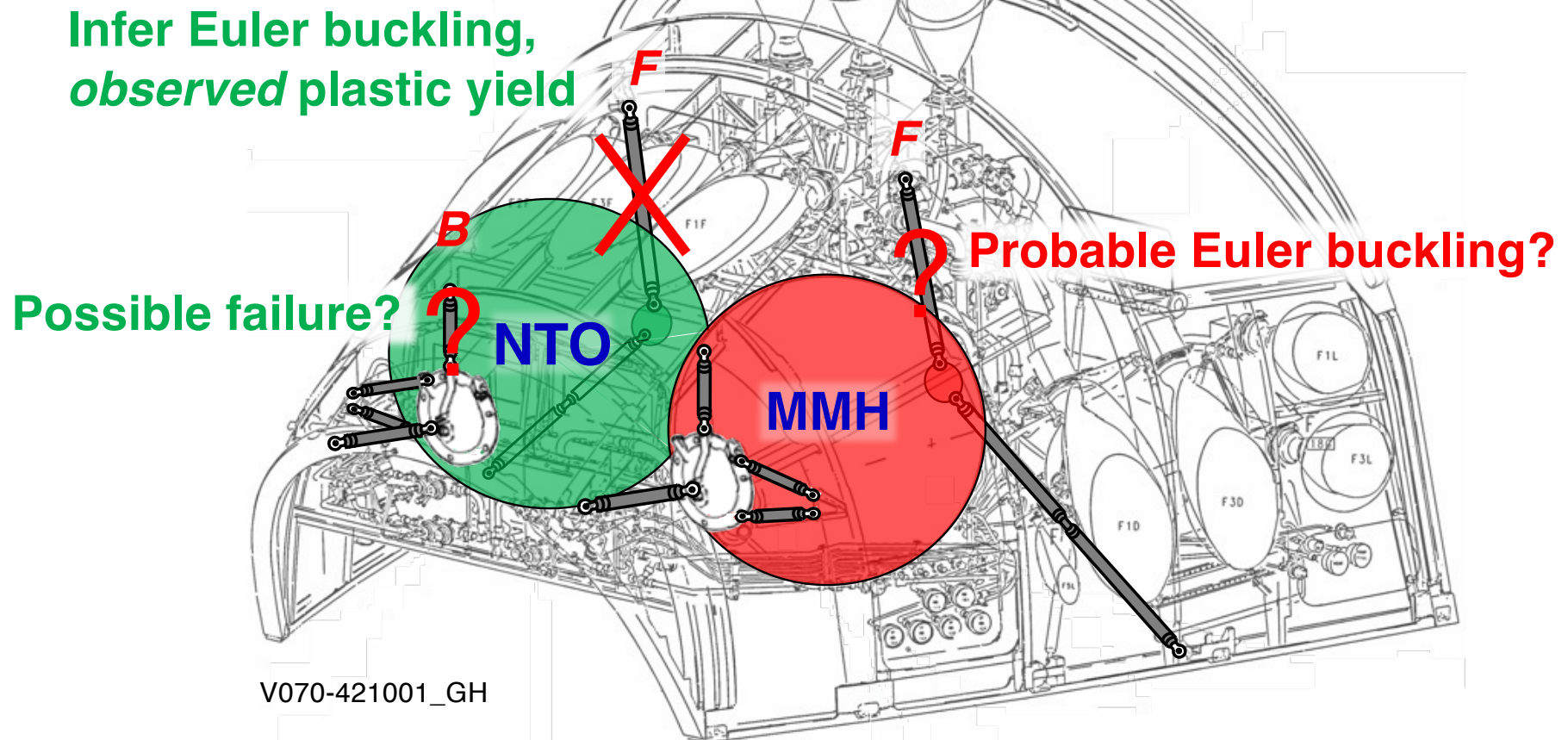
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- Estimate DAF = 1.86 to fail NTO Strut *B*  
 => **Possible NTO Strut *B* buckling**
- Now consider MMH Strut *F*
  - $P_F = -900 \text{ lbm} \times 5.24 \text{ g}/(2 \times 5), \times 1.57$   
 $= -4213 \text{ lbf} < P_{\text{euler}} (-4142 \text{ lbf})$
  - => **Probable MMH Strut *F* buckling**
- However no corroborating evidence of these failures observed on flight hardware
- MMH Strut *B* failure unlikely (DAF = 2.87)

# FRCS Failed Support Struts



# Linear Static and Buckling Analyses

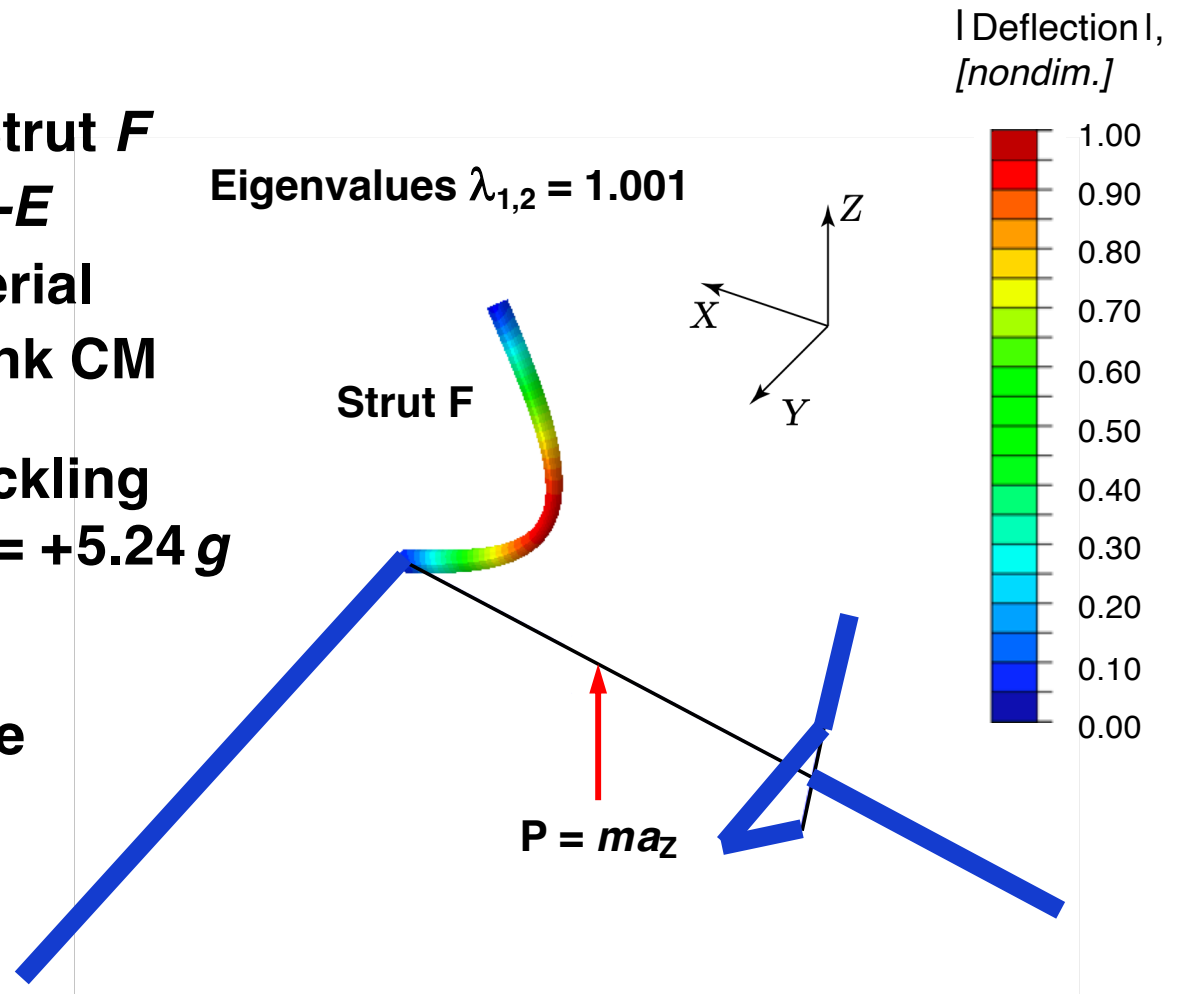
## Analysis assumptions

- Tube of plate elt's for Strut *F*
- Beam elt's for Struts *A-E*
- Linear Ti-3Al-2.5V material
- Constant Z-accel. at tank CM

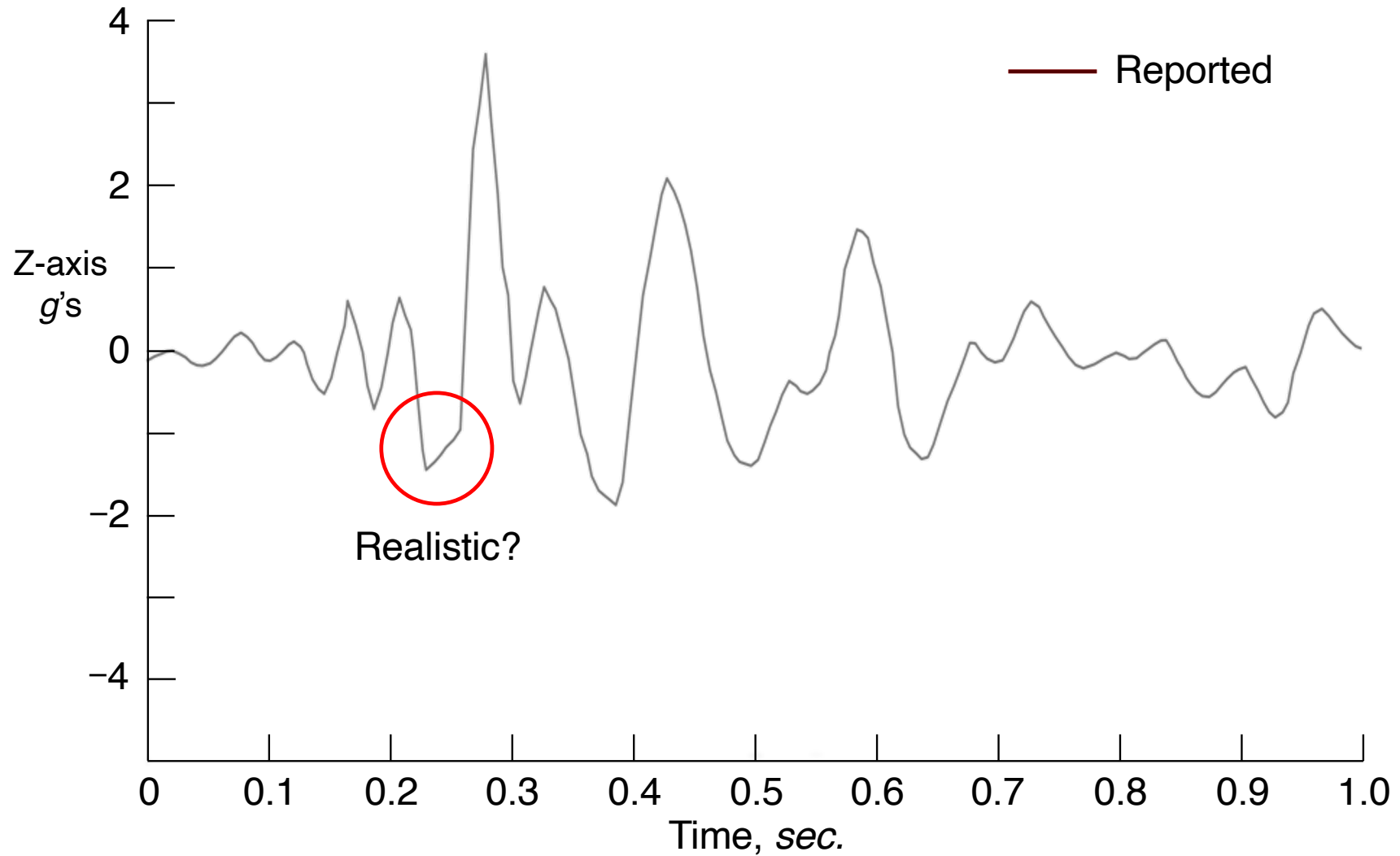
## Compute Strut *F* Euler buckling

$P_F^{cr} = -4142 \text{ lbf}$  from  $a_z = +5.24 g$   
applied at tank CM

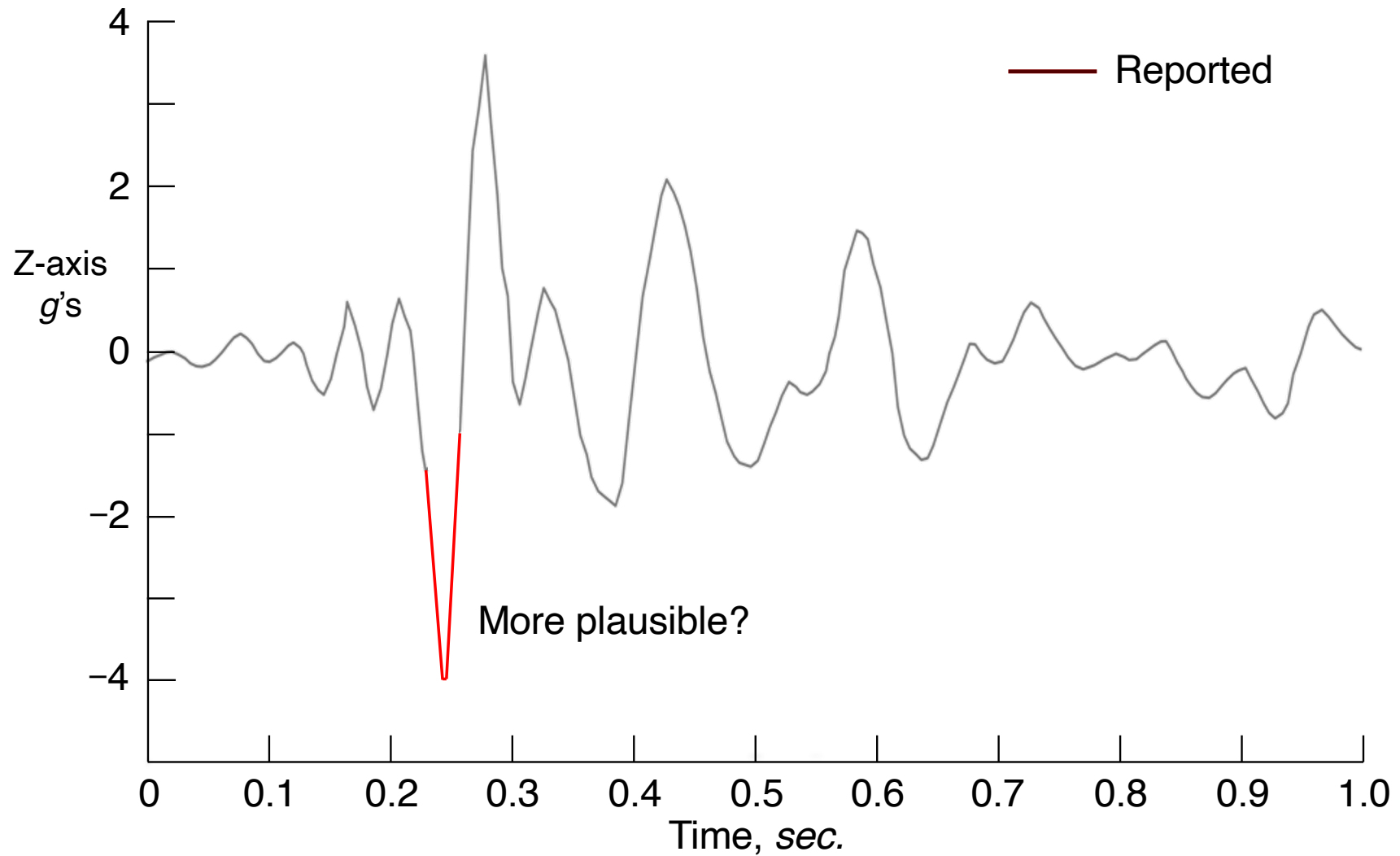
Abaqus FE results validate  
closed-form analyses



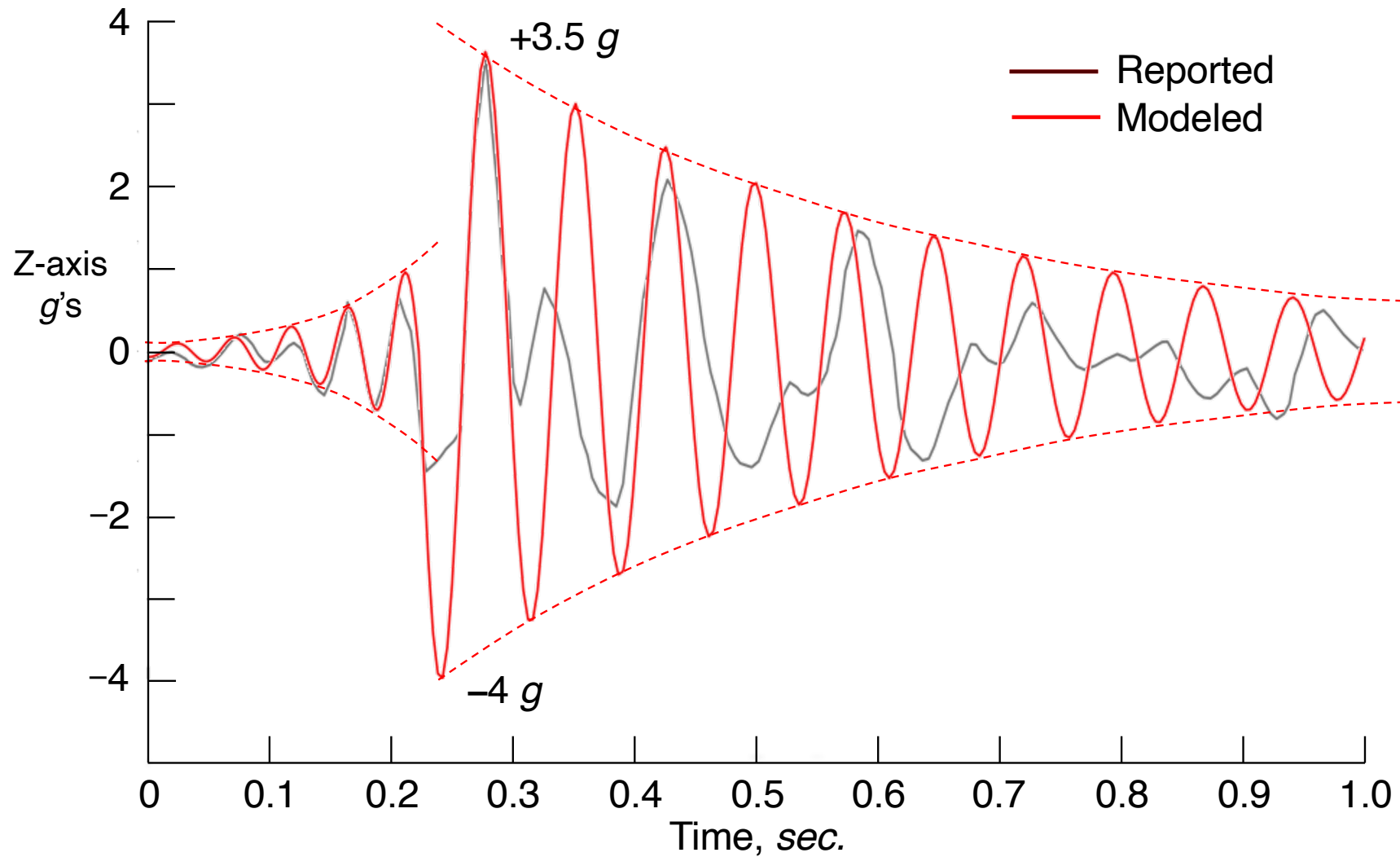
# Nonlinear Dynamic Analysis – Sinusoidal Input



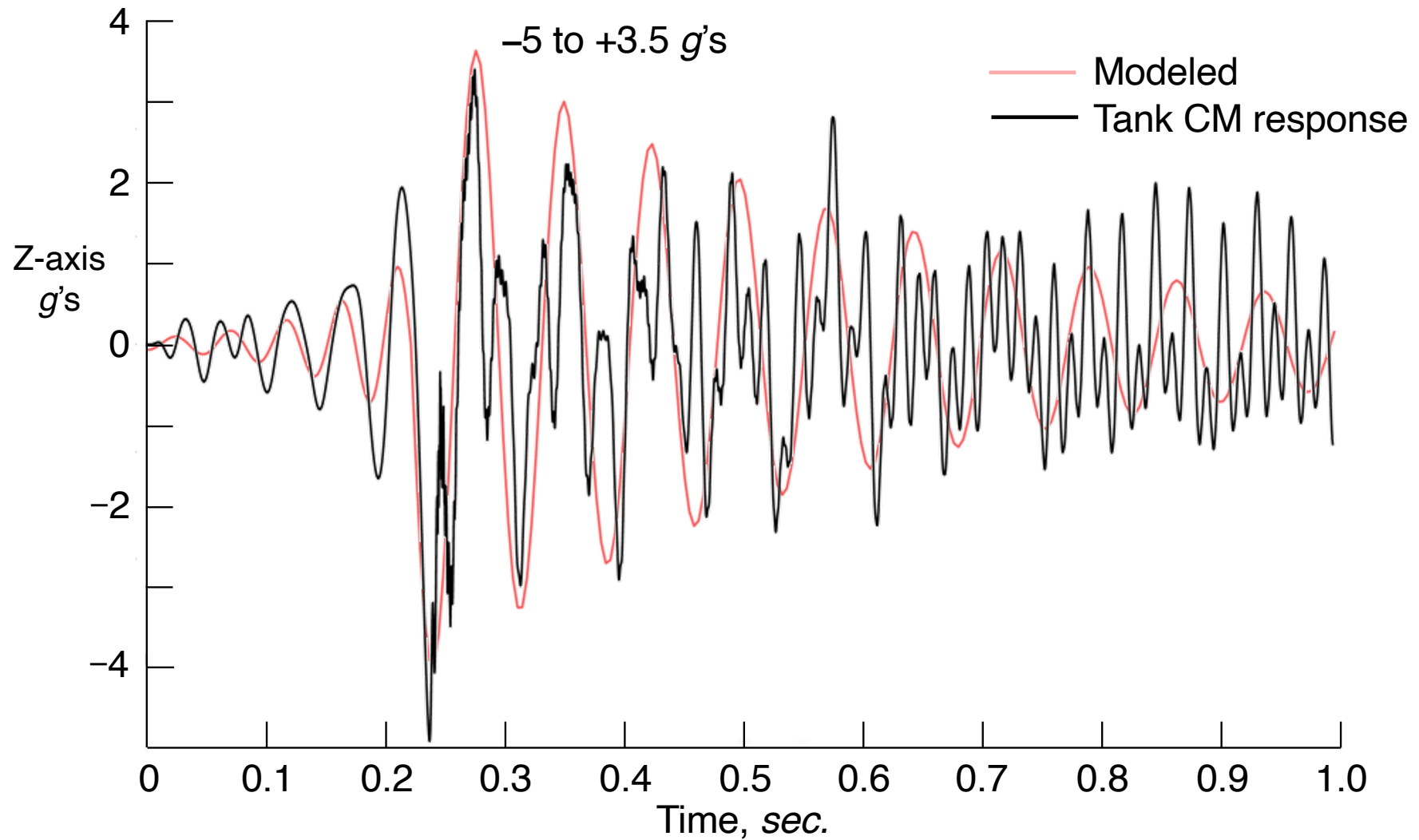
## Nonlinear Dynamic Analysis – Sinusoidal Input (2)



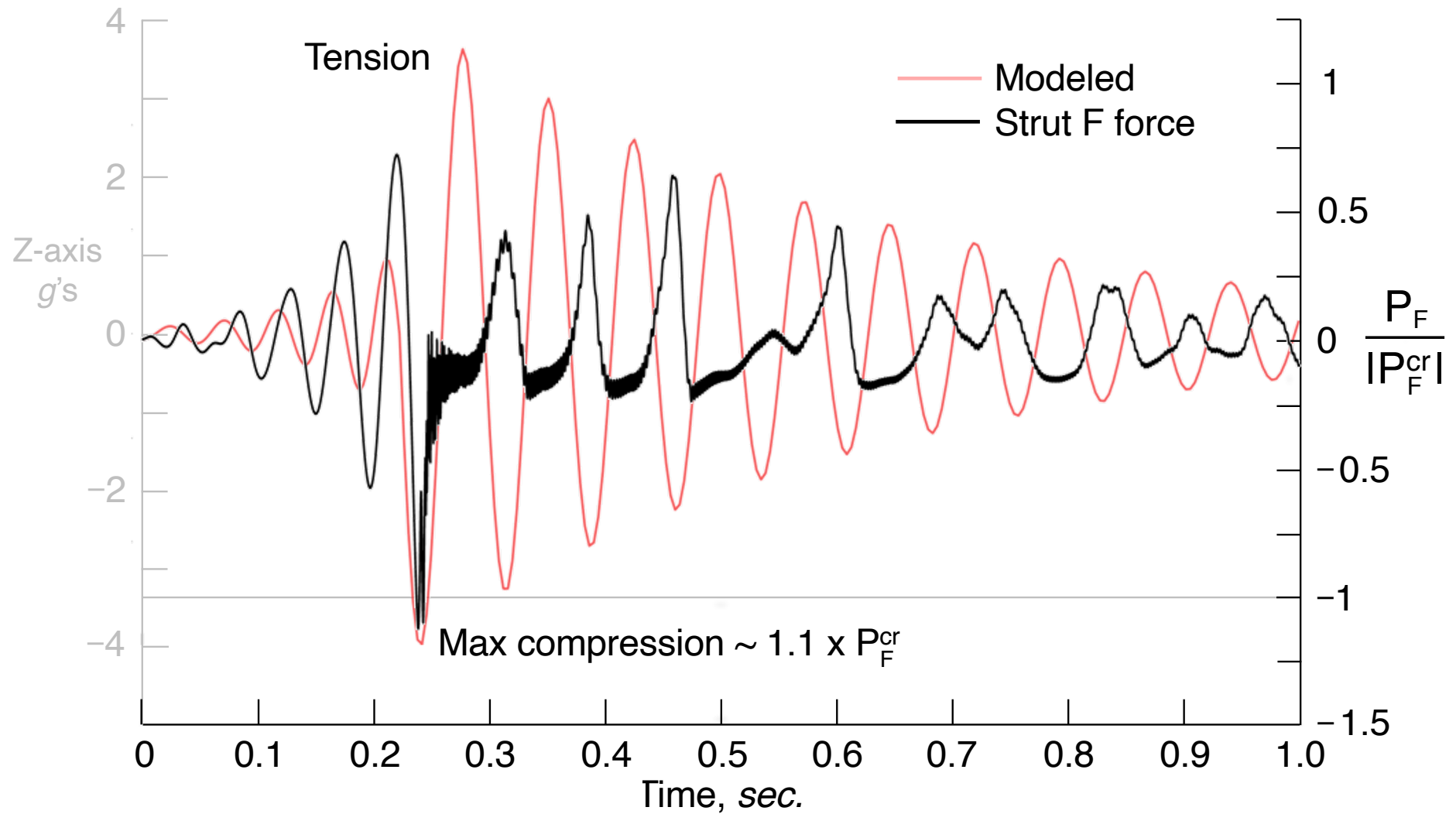
## Nonlinear Dynamic Analysis – Sinusoidal Input (3)



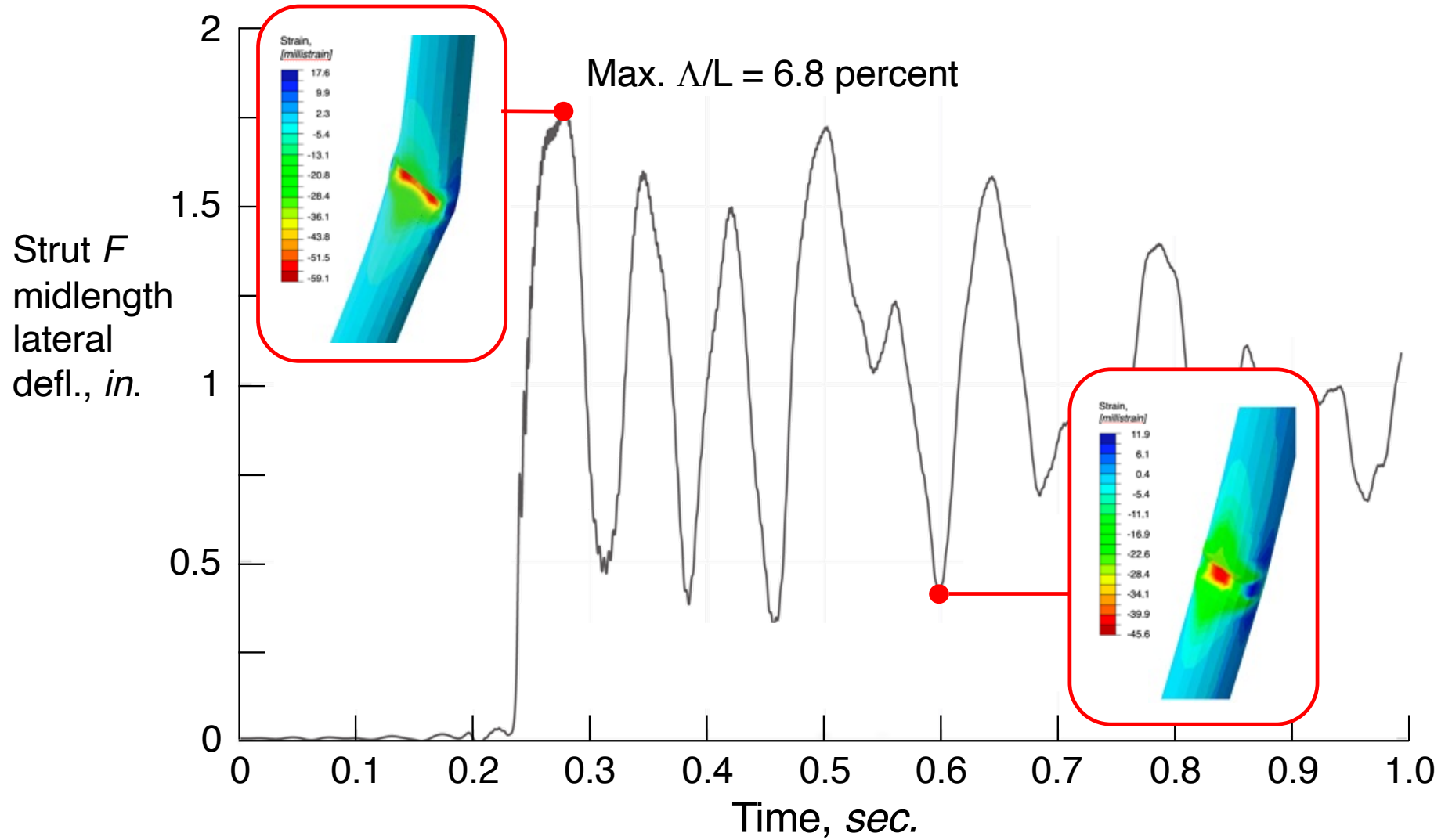
# Analysis Results – Sinusoidal Input



## Analysis Results – Sinusoidal Input (2)



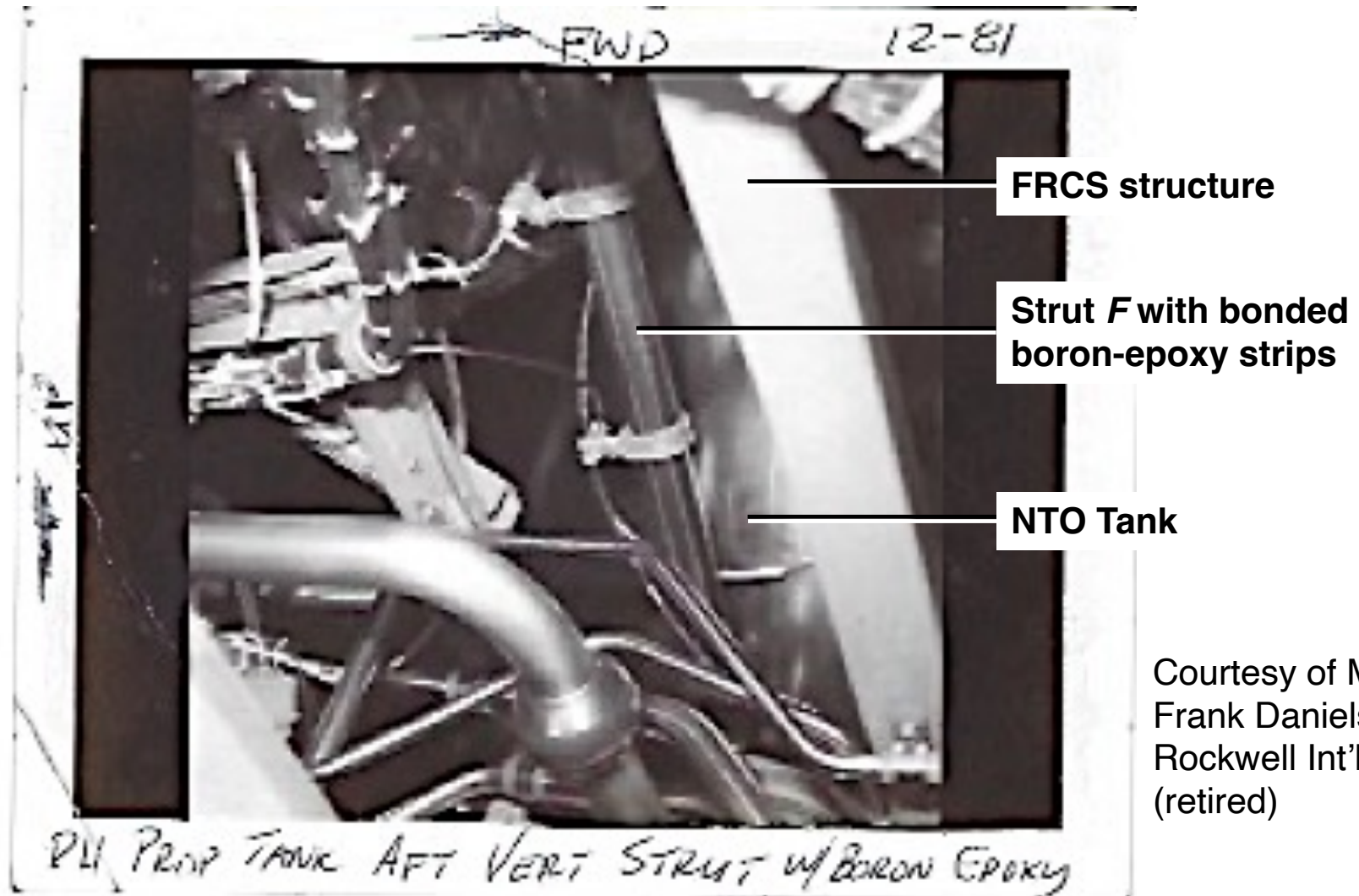
## Analysis Results – Sinusoidal Input (3)



## Concluding Remarks

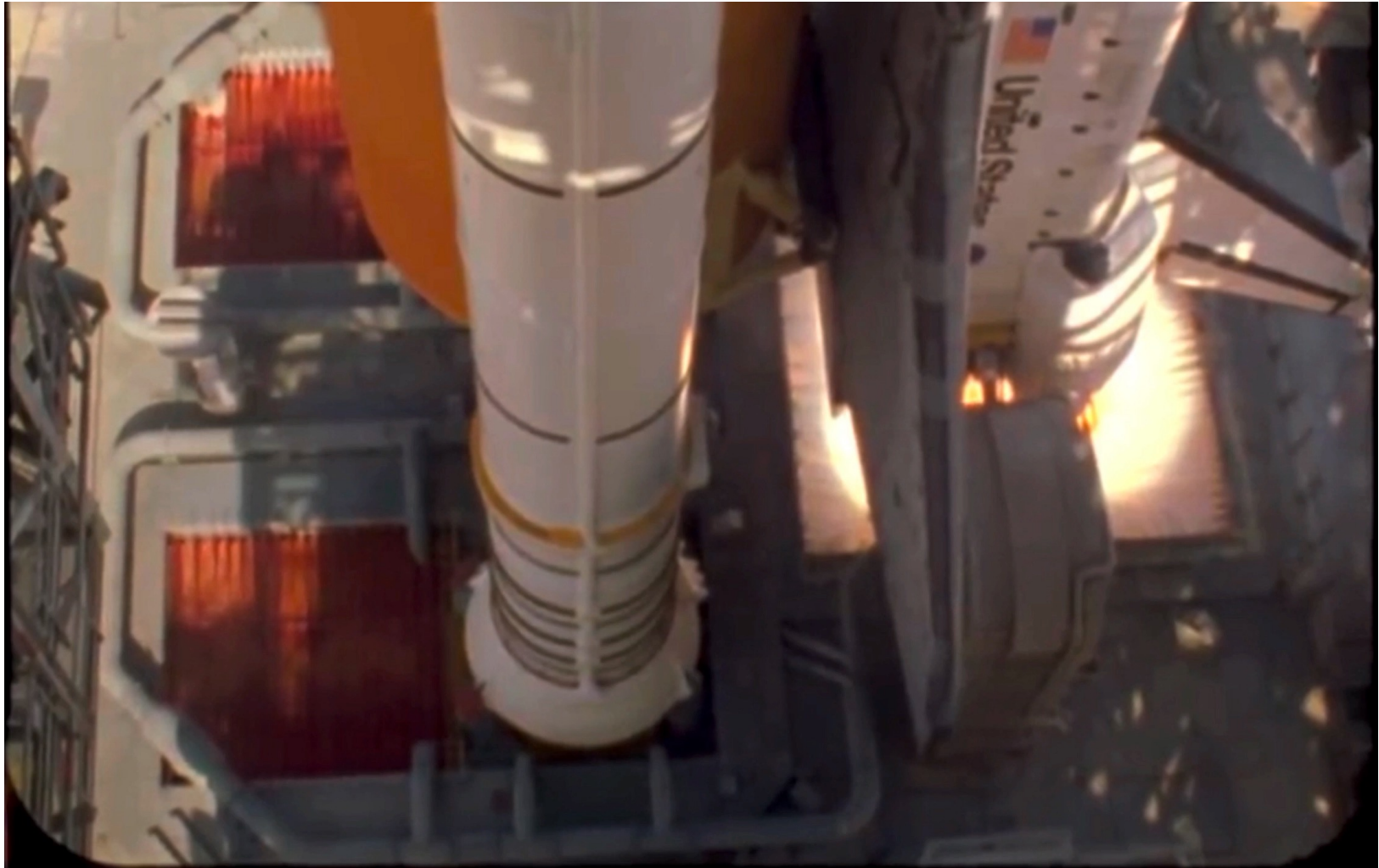
- Forward RCS NTO Strut *F* damage found during STS-1 post-flight inspection
- Classical analyses of Strut *F* performed to estimate strain energies for Euler buckling and initial yield
- Nonlinear structural analyses validate Strut *F* Euler buckling and plastic yielding
- Additional analyses suggest *possible* NTO Strut *B* failure, and *probable* MMH Strut *F* failure
- Mitigations for STS-2 and all subsequent flights
  - Boron-epoxy stiffeners added to all Struts *B* and *F*
  - Increased pad water suppression and injection
- No recurrence over next 30 years and 134 flights!

## FRCS NTO Strut *F*, pre-STS-2



Courtesy of Mr.  
Frank Daniels,  
Rockwell Int'l  
(retired)

## Sound Suppression Water System, post-STS-1

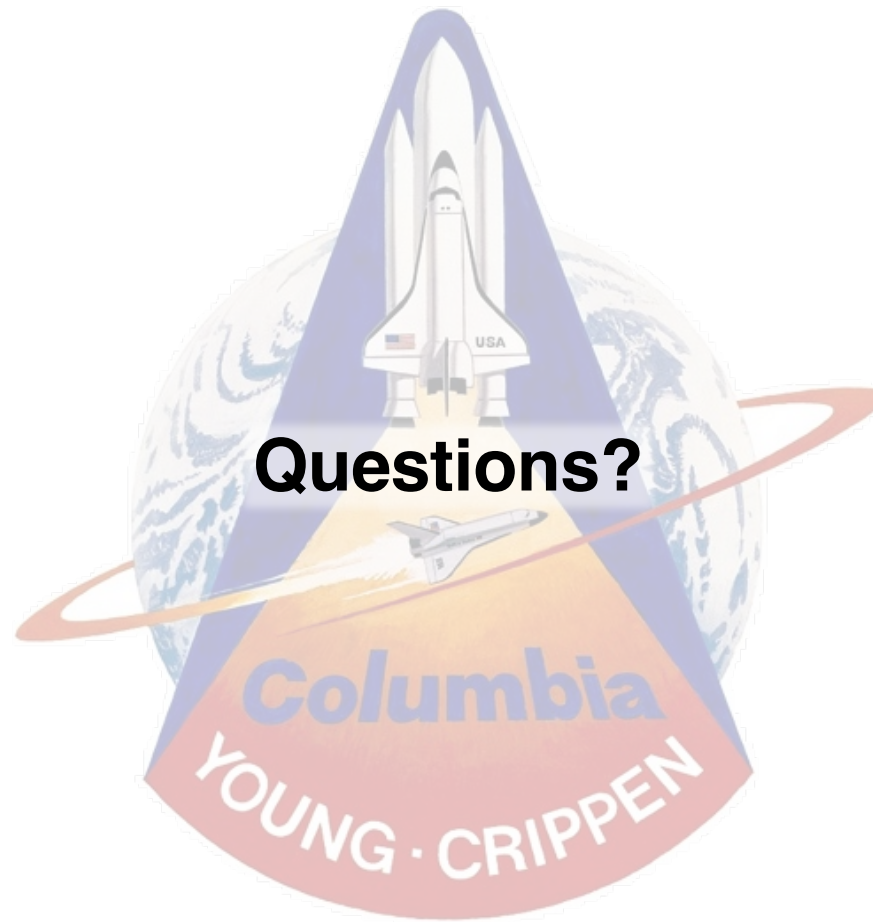


Credit: NASA/KSC

***“We Just Became Infinitely Smarter”***



Credit: NASA/JSC



**Questions?**