

Dynamic Design Analysis Method to Evaluate Shipboard Shock in LS-DYNA®

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Abstract

The Dynamic Design Analysis Method (DDAM) provides a method for analyzing shipboard components that are subjected to a shock event due to an underwater explosion. Typically, these events are caused by a near miss explosion that results in a severe shock event due to the transient motion of the ship or submarine from the forces imparted on the hull of the vessel.

*This work will investigate the procedure for conducting DDAM in LS-DYNA through the use of the *CONTROL_IMPLICIT_EIGENVALUE and *FREQUENCY_DOMAIN_RESPONSE_SPECTRUM cards. Specifically, a demonstration problem will be shown where the modes and mass participations are extracted through an eigenvalue analysis. These extracted values are then used to calculate an acceleration versus frequency curve using the DDAM procedure. Through a response spectrum analysis using the base acceleration curve developed, the stresses in the component can then be calculated from the shock event. Finally, these results will be compared to other solvers to demonstrate that LS-DYNA accurately conducts a DDAM analysis.*

Introduction

The Dynamic Design Analysis Method (DDAM) provides a method for analyzing shipboard components for survivability in the case of a near miss underwater explosion. The foundation of DDAM traces its roots to the 1960's where experimental data was used to develop a method to analyze components through a series of hand calculations. This method became formalized in 1976 with the document NAVSEA 0908-LP-000-3010 (Shock Design Criteria for Surface Ships). With the accessibility of cheap, robust computing systems and well developed finite element codes in the 90's, the procedure was revised in 1995 to account for and provide guidelines for the use of finite element analysis when conducting a DDAM analysis [1].

In order to demonstrate how to conduct a DDAM analysis in LS-DYNA, this paper will initially provide a brief overview of the theory and procedure that encompasses DDAM. The DDAM procedure can essentially be narrowed into three phases: modal analysis and assessment, coefficient computation, and response spectrum analysis. It should be noted that NAVSEA 0908-LP-000-3010 goes into great detail on these phases as well as the model setup and evaluation of the results. It should always be consulted when conducting a DDAM analysis, as many caveats exist. For brevity, this paper will simply focus on the components of a DDAM analysis that pertain to the LS-DYNA solver.

An overview of the DDAM procedure as done in LS-DYNA follows and will be explained in greater detail later in this paper. The first phase is completed by conducting a modal analysis using the *CONTROL_IMPLICIT_EIGENVALUE card. The second phase requires all of the necessary data from the modal analysis to be extracted and have the DDAM equations applied to develop a frequency versus acceleration curve. Lastly, the third phase is completed by conducting a response spectrum analysis using the *FREQUENCY_RESPONSE_SPECTRUM card using the previously developed curve. The response spectrum analysis can then be used to determine the stresses imparted on the structure from a shock event. Furthermore, a

simple tool developed at the Naval Surface Warfare Center - Dahlgren Division (NSWCDD), to streamline this process will be demonstrated.

Finally, a comparison of results from a typical DDAM analysis conducted in LS-DYNA will be compared to results obtained in ANSYS and Optistruct. This comparison is intended to benchmark the LS-DYNA solver to other solvers with integral DDAM capabilities.

DDAM Procedure

Modal Analysis and Assessment

The first step in conducting a DDAM analysis in LS-DYNA is to conduct a modal/eigenvalue analysis. This is conducted through the use of the card `*CONTROL_IMPLICIT_EIGENVALUE`. Detailed explanations and recommendations can be found in “Guideline for Implicit Analyses using LS-DYNA” by DYNAmore Nordic, which is an excellent reference for all implicit analyses [2]. When setting up the card `*CONTROL_IMPLICIT_EIGENVALE`, as seen in Figure 1, the number of eigenvalues extracted must be sufficient to attain at least 80% accumulated modal effective mass in the x, y and z directions. Furthermore, `MSTRES` should be set to 1 in order to calculate stresses, which will be used in the response spectrum analysis. Furthermore, a cut-off frequency may be specified using the `RHTEND` flag. NAVSEA 0908-LP-000-3010 recommends a cut-off frequency of 250 Hz, with the caveat that if the 80% accumulated modal effective mass is not attained, the cut-off frequency should be increased. Discussion of the other options on the card can be seen in the LS-DYNA User’s Manual [3].

	NEIG	CENTER	LFLAG	LFTEND	RFLAG	RHTEND	EIGMTH	SHFSC
1	30	0.0	0	-1.000e+029	0	1.000e+029	2	0.0
	ISOLID	IBEAM	ISHELL	ITSHLL	MSTRES	EVDUMP	MSTRSCL	
2	0	0	0	0	1	0	0.0100000	

Figure 1: Setup of `*CONTROL_IMPLICIT_EIGENVALUE` card.

Once the modal analysis has been completed, the results should be assessed using the eigout file that is produced from the simulation. For each direction, the significant modes should be extracted in order to be used for the coefficient computation phase and response spectrum analysis phases. This occurs with the following procedure.

1. Extract significant modes (>1% modal effective mass) in each direction.
2. Determine if the sum of the effective mass of the significant modes is >80% in each direction. If less than 80%, extract more modes and/or increase the cut-off frequency.

During this process, the following conditions should also be noted, as they may exceed the requirements or limitations of DDAM. Closely spaced modes will be discussed in the response spectrum phase.

1. Determine if closely space modes (modes within 10% of a mean frequency) exist in each direction.
2. Determine if a mode exists in any direction that is less than 5 Hz.

An example eigout file can be seen in Figure 2. As seen in this file, 15 modes were extracted for this specific model. From the procedure listed above, the significant modes would be extracted, as seen in Figure 3. As seen from these significant modes, the sum of the z-direction modes is less than 80%, requiring more modes to be extracted. Furthermore, closely spaced modes exist in both the y and z directions.

MODAL EFFECTIVE MASS

MODE	X-TRAN		Y-TRAN		Z-TRAN	
	Eff. Mass	Accum. %	Eff. Mass	Accum. %	Eff. Mass	Accum. %
1	1.473739E+00	75.08%	1.830071E-04	0.01%	5.901467E-06	0.00%
2	2.681935E-04	75.09%	1.319105E+00	67.21%	1.478343E-05	0.00%
3	3.278492E-02	76.76%	6.977164E-03	67.57%	3.702264E-05	0.00%
4	2.251232E-01	88.23%	2.930085E-03	67.72%	1.101513E-04	0.01%
5	1.206923E-03	88.29%	1.999196E-01	77.90%	1.319189E-03	0.08%
6	1.114399E-02	88.86%	9.994242E-04	77.95%	5.277894E-01	26.96%
7	1.392553E-01	95.96%	2.705584E-04	77.97%	4.632393E-03	27.20%
8	6.075412E-05	95.96%	1.034803E-04	77.97%	4.398932E-01	49.61%
9	1.193514E-03	96.02%	1.759957E-03	78.06%	1.769685E-01	58.63%
10	1.049101E-02	96.55%	1.115058E-01	83.74%	1.938275E-01	68.50%
11	2.578036E-05	96.56%	6.776876E-04	83.78%	2.213432E-05	68.50%
12	4.184503E-06	96.56%	3.689567E-04	83.79%	8.343578E-04	68.54%
13	7.445418E-05	96.56%	3.347760E-03	83.97%	2.380536E-02	69.76%
14	3.747878E-03	96.75%	1.245781E-01	90.31%	1.424868E-01	77.02%
15	1.808933E-03	96.84%	4.243366E-02	92.47%	7.268815E-03	77.39%

Figure 2: Example eigout file from an eigenvalue analysis. Model units: lbf-s²/in, in, s.

Significant X-Modes			Significant Y-Modes			Significant Z-Modes		
Frequency	Eff Mass	%	Frequency	Eff Mass	%	Frequency	Eff Mass	%
46.95	1.47E+00	75.08%	52.33	1.32E+00	67.20%	215.52	5.28E-01	26.89%
126.74	3.28E-02	1.67%	173.86	2.00E-01	10.18%	236.19	4.40E-01	22.41%
150.7	2.25E-01	11.47%	282.5	1.12E-01	5.68%	262.0	1.77E-01	9.02%
219.5	1.39E-01	7.09%	311.6	1.25E-01	6.35%	282.5	1.94E-01	9.87%
			313.8	4.24E-02	2.16%	300.2	2.38E-02	1.21%
						311.6	1.42E-01	7.26%
Cumulative % Mass		95.31%	Cumulative % Mass		91.58%	Cumulative % Mass		76.66%

Figure 3: Significant modes extracted from eigout. Model units: lbf-s²/in, in, s.

Coefficient Computation Phase

Once the significant modes have been extracted, the second phase is conducted, which will build frequency vs. acceleration plots for each direction based on the significant modes. This process along with the unclassified equations and coefficients can be found in the U.S. Naval Research Laboratory (NRL) Memorandum Report 1396 “Interim Design Values for Shock Design of Shipboard Equipment” which will be used in this paper [4]. In order to conduct this phase, the following information is required:

1. Vessel Type: Submarine or Surface
2. Mounting Type: Deck, Hull, or Shell Plate
3. Analysis Type: Elastic or Elastic Plastic

Detailed explanations of this information can be found in both references [1] and [4]. This paper will examine a case with a surface ship, where the equipment is deck mounted, and an elastic analysis type. In order to calculate the accelerations for each significant mode, the following procedure takes place:

1. The modal effective mass, W_a , for the mode being analyzed is converted to thousands of pounds, or kips.
2. The acceleration, A_o , and velocity, V_o , is calculated from the reference equations in NRL-1396 based on the vessel type and mounting type.
3. A_o and V_o are then multiplied by the design values that correspond to the direction of the mode and the analysis type, to produce A_a and V_a .
4. A_a is multiplied by 386 in/s^2 and V_a is multiplied by the frequency of the mode in radians per second.
5. The acceleration for this mode, D_a , is the lesser of A_a and V_a . If both are below $6g$'s or 2316 in/s^2 , the value of D_a is $6g$'s or 2316 in/s^2 .

For the case of a surface ship, deck mounted, elastic analysis, NRL Memorandum Report 1396 would yield the following reference equations and design values.

$$A_o = 10 \left[\frac{(37.5 + W_a)(12 + W_a)}{(6 + W_a)^2} \right]$$

$$V_o = 30 \left[\frac{(12 + W_a)}{(6 + W_a)} \right]$$

	<u>Elastic</u>	
	A_a	V_a
Vertical	1.0 A_o	1.0 V_o
Athwartships	0.4 A_o	0.4 V_o
Fore and Aft	0.4 A_o	0.4 V_o

From the eigout and significant modes shown previously, it is then possible to calculate the acceleration at each mode for each direction. For instance, the first mode in the x-direction would be the following:

$$W_a = \left(1.47 \frac{\text{lb} \cdot \text{ft} \cdot \text{s}^2}{\text{in}} \right) \left(386 \frac{\text{in}}{\text{s}^2} \right) \left(\frac{1}{1000} \frac{\text{kips}}{\text{lb} \cdot \text{ft}} \right) = 0.56742 \text{ kips}$$

$$A_o = 10 \left[\frac{(37.5 + 0.56742)(12 + 0.56742)}{(6 + 0.56742)^2} \right] = 110.92 \text{ g}$$

$$V_o = 30 \left[\frac{(12 + 0.56472)}{(6 + 0.56472)} \right] = 57.408 \frac{\text{in}}{\text{s} \cdot \text{rad}}$$

In order to use the design equations, it must be known what the direction being analyzed is relative to the vessel it is being mounted on. For this example, the mode analyzed is in the x-direction and it is known that the x-direction of the model corresponds to the fore-aft direction of the ship. The y-direction will correspond to the athwartships direction and the z-direction will correspond to the vertical direction. From this, we can use the design values to determine our accelerations.

$$A_a = 0.4A_0 = 0.4(110.92g) = 44.37g = 17126 \frac{in}{s^2}$$

$$V_a = 0.4V_0 = 0.4 \left(57.408 \frac{in}{s} \right) = 22.963 \frac{in}{s} = \left(22.963 \frac{in}{s} \right) (46.95 Hz)(2\pi) = 6774 \frac{in}{s^2}$$

Since D_a is the minimum of A_a and V_a , D_a would equal 6774 in/s^2 .

This process would be conducted for each mode in each direction, which would yield the following results for frequency versus acceleration seen in Table 1.

Table 1: Frequency vs. Acceleration for x, y, and z directions.

X- Direction (Fore-Aft)		Y-Direction (Athwartship)		Z-Direction (Vertical)	
Frequency (Hz)	Acceleration (in/s^2)	Frequency (Hz)	Acceleration (in/s^2)	Frequency (Hz)	Acceleration (in/s^2)
46.94956	6774	52.33049	7583	215.521	46148.6
126.7363	19091	173.8624	18973	236.1886	46486.0
150.7064	18932	282.5073	19116	262.0197	47524.8
219.4635	19071	311.5756	19095	282.5073	47456.8
		313.7767	19230	300.2146	48151.2
				311.5756	47664.4

Response Spectrum Analysis

Once the frequency versus acceleration curves have been computed, it is then possible to compute the dynamic phase of the DDAM process using the *FREQUENCY_DOMAIN_RESPONSE_SPECTRUM card. The first step would be to construct a *DEFINE_CURVE card with the frequency and acceleration values of interest, as seen in Figure 4.

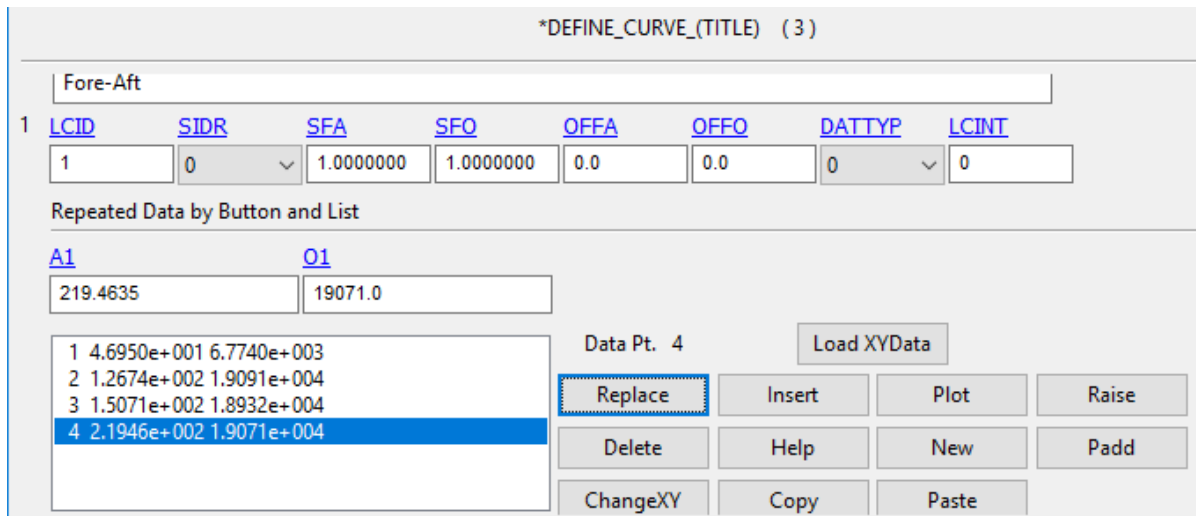


Figure 4: *DEFINE_CURVE card of Fore-Aft Frequencies and Accelerations.

Once completed, the *FREQUENCY_DOMAIN_RESPONSE_SPECTRUM card can be added to the deck, as seen in Figure 5. In order to properly conduct the DDAM, the field MCOMB must use type 4, which is the NRL summation method. When closely spaced modes exist, NAVSEA 0908-LP-000-3010 provides an alternative method to combine those modes, aptly called the Closely Spaced Modes (CSM) method. This method is useful if the two closely spaced modes have large effective modal masses in the same direction,

which may result in unrealistic responses in the model. Currently, the CSM method is unavailable in LS-DYNA, but it is anticipated that it will be available in a future version.

The fields MDMIN, MDMAX, FNMIN, and FNMAX should be set appropriately to cover the modes and frequencies from the significant modes generated. This card also allows you to use the previous eigenvalue results by setting the RESTRT field to 1 and using *FREQUENCY_DOMAIN_PATH card, if appropriate. Critical or Rayleigh damping may be added through DAMPF or DMPMAS and DMPSTF. NAVSEA 0908-LP-000-3010 provides guidance on the use of damping in the analysis. Finally, LCTYP=1 would be set to indicate a base acceleration, the appropriate degree of freedom (DOF) would be set in DOF, the load curve selected in LC/TBID, and a scale factor may be applied in field SF if any unit conversion must take place.

*FREQUENCY_DOMAIN_RESPONSE_SPECTRUM (1)							
1	MDMIN	MDMAX	FNMIN	FNMAX	RESTRT	MCOMB	
	1	30	0.0	500.00000	1	4	
2	DAMPF	LCDAMP	LDTYP	DMPMAS	DMPSTF		
	0.0	0	0	0.0	0.0		
Repeated Data by Button and List							
	LCTYP	DOF	LC/TBID	SF	VID	LNID	LNTYP
	1	1	1	1	0	0	1
							2

Figure 5: Typical *FREQUENCY_DOMAIN_RESPONSE_SPECTRUM card for DDAM.

NSWCDD LS-DYNA DDAM Application

Conducting the DDAM procedure can be very time intensive when processing the modal results and calculating the accelerations by hand. In order to streamline the process, an application was developed at NSWCDD to expedite the process. The graphical user interface allows the user the ability to select the folder with the results from the eigenvalue analysis. Once selected, the application will automatically load the eigout file and extract the mass of the system from the d3hsp file. Once the results are loaded from the eigout folder, the user can select the vessel type, mounting type, and analysis type from the panel and click on the Results button. This will automatically process the eigout file, extract the significant modes, and calculate the accelerations for each of the significant modes. Furthermore, the application will create a .k with the *DEFINE_CURVE card populated with the frequency vs. acceleration data that can easily be included in the subsequent response spectrum analysis with the card *INCLUDE. Finally, the application will provide warnings for closely spaced modes, frequencies below 5 Hz, and if the total effective mass is below 80%.

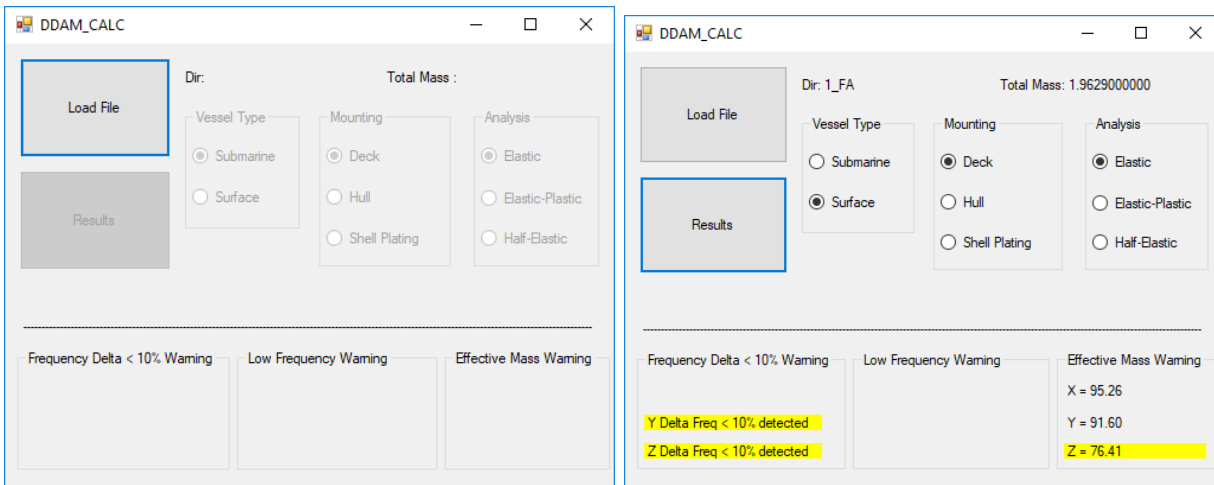


Figure 6: NSWCDD DDAM Application graphical user interface.

Model Comparison

In order to validate this procedure and benchmark LS_DYNA, a DDAM analysis was conducted in LS-DYNA, ANSYS, and Optistruct in order to compare the results. The first test consisted of a simple cantilevered tube modelled as a shell with the shock direction applied in the vertical direction. From the results in Figure 6, it can be seen that the stress contours are nearly identical and the peak stresses, as seen in Table 2, are within 1% of Optistruct and within 3% of ANSYS.

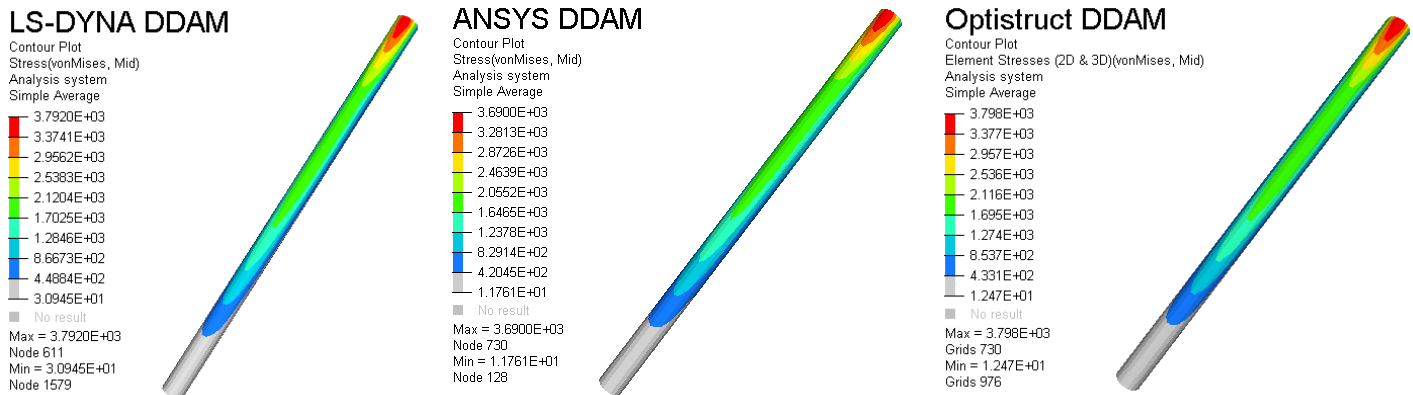


Figure 7: DDAM analysis of a cylindrical tube in LS-DYNA, ANSYS, and Optistruct.

Table 2: Maximum stress in cylinder model and comparison of results between LS-DYNA, ANSYS, and Optistruct.

Cylinder Model DDAM Comparison			
Solver	LS-DYNA	ANSYS	Optistruct
Max Stress (psi)	3792	3690	3798
% Difference from LS-DYNA	-	2.69%	0.16%

A second validation and benchmarking test was conducted with a more complex structure that was modelled using shells. The models utilize the same mesh in each solver with components simplified to point masses connected with rigid elements to the structure and welds modelled as multiple tied (bonded) contacts between the lower order shell elements of the structure. As seen in Figure 7, the stress contours between all three models

are nearly identical. The highest stresses in the ANSYS model and the lowest stresses in the Optistruct model, as seen in Table 3, are within 5% of the LS-DYNA model.

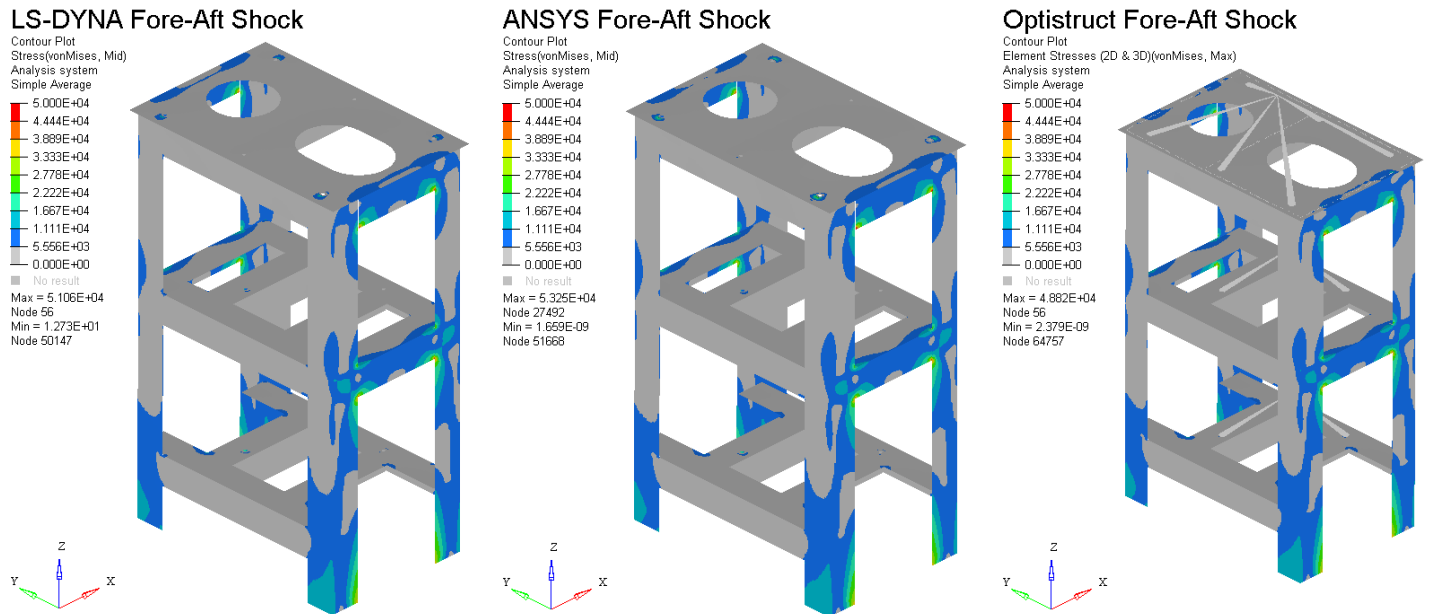


Figure 8: DDAM analysis of an assembly with LS-DYNA, ANSYS, and Optistruct.

Table 3: Maximum stress in assembly model and comparison of results between LS-DYNA, ANSYS, and Optistruct.

Assembly Model DDAM Comparison			
Solver	LS-DYNA	ANSYS	Optistruct
Max Stress (psi)	51063	53245	48820
% Difference from LS-DYNA	-	4.27%	4.39%

Conclusion

The Dynamic Design Analysis Method (DDAM) is used by the U.S. Navy to analyze equipment for shock survivability. LS-DYNA is a robust solver that has the capability to conduct the DDAM analyses with results comparable to other solvers. The results from the test cases analyzed in LS-DYNA, ANSYS, and Optistruct yielded a highest percent difference of 4.39%. The test cases have built confidence in the procedure to perform DDAM analyses in LS-DYNA. Additionally, it has been announced that LSTC developers are currently developing a DDAM specific *FREQUENCY_DOMAIN_RESPONSE_SPECTRUM card that will conduct the procedure internal to LS-DYNA.

References

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