Benchmarks for submerged structure response to underwater explosions

Hans U. Mair
Institute for Defense Analyses, Operational Evaluation Division, 1801 North Beauregard Street, Alexandria, VA 22311-1772, USA
E-mail: mairh@asme.org

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Benchmarks for submerged structure response to underwater explosions (UNDEX) are compiled. Both analytical and empirical benchmarks are presented; each type has advantages and disadvantages for the purposes of model validation, though no methodology for employing these benchmarks in a model validation effort is proposed. Benchmark computations are also referenced as part of this compilation. Finally, extension of this compilation to the UNDEX response of internal equipment and floating structures, and to hydrodynamic/hydraulic ram problems, is proposed.

1. Overview

A set of underwater explosion (UNDEX) benchmarks is compiled, in the spirit of similar compilations [1–4], and in the interest of initiating a dialog within the UNDEX community on validation techniques. Focus is limited to the response of submerged structures to underwater explosions (including structures and explosions in saturated sand), and only unclassified data are included.

Use of the term "benchmarks" is admittedly not consistent with that in the more mature fields of computational fluid and structural dynamics, in which the term is applied only to data of quantified high accuracy and repeatability. It is deemed necessary here to include data being employed as benchmarks, even though their accuracy and repeatability have not been quantified.

Both analytical and empirical benchmarks are presented; each type has advantages and disadvantages. One issue raised in this compilation is the quality and applicability of validational data, specifically the added value of converged analytical models, replicate experiments, and quantification of empirical scatter. This document does not propose a methodology for employing these benchmarks in a model validation effort.

Several tables summarize the characteristics of the benchmarks, and a table of benchmark computations is also presented. For simplicity, a binary identification is employed, where $\bullet$ = "yes", and $\circ$ = "no". In this preliminary compilation, the minimal detail provided about the benchmarks does not include response characteristics. Such characterization would be extremely useful for identifying phenomena of interest to the community, benchmark limitations and applicability, and duplicate and missing benchmark data.

2. Descriptions of benchmark problems

Two classes of benchmarks are described: analytical (summarized in Table 1) and empirical (summarized in Table 2). One-dimensional (1D) benchmark data provide the simplest and most affordable validation, but cannot exhibit many of the phenomena of greatest interest to the underwater explosion structure/medium interaction community. Two-dimensional (2D) benchmarks can exhibit many of the phenomena of interest to the underwater explosion structure/medium interaction community. Some phenomena of interest to the underwater explosion structure/medium interaction community can only be exhibited in 3D (e.g., failure and fracture of stiffened cylinders); however, computational modeling of 3D events is more demanding than that of 1D and 2D events. Continuum dynamics and structure/medium interaction benchmarks are described in more detail in Table 3 and Table 4, respectively.

2.1. Analytical benchmarks

Analytical benchmarks, listed in Table 1, are not experiments. Ideally, they are the solution to a system of mathematical equations with appropriate bound-

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Table 1

Overview of analytical benchmarks

	Exact/Converged	1D Spherical	1D Cartesian	1D Cylindrical	2D Cartesian	2D Axisymmetric	3D Cartesian
Shock Tube	●	○	●	○	○	○	○
Rayleigh-Plesset Solution	●	●	○	○	○	○	○
Primakoff Solution	●	●	○	○	○	○	○
Cavitated Water Impact	●	○	●	○	○	○	○
P-alpha Shock Tube	●	○	●	○	○	○	○
Wardlaw/Mair Bubble	●	●	○	○	○	○	○
Taylor Plate	●	○	●	○	○	○	○
Schechter/Bort Plates	●	○	●	○	○	○	○
Snay/Christian Plate	○	○	●	○	○	○	○
Bleich/Sandler Plate	○	○	●	○	○	○	○
Huang Plate	○	○	○	○	○	●	○
Murray Cylinder	●	○	○	○	●	○	○
Huang Sphere	●	○	○	○	○	●	○
Huang Concentric Spheres	○	○	○	○	○	●	○
Huang Cylinder	○	○	○	○	●	○	●
Huang Concentric Cylinders	○	○	○	○	●	○	○
Zhang/Geers Sphere	○	○	○	○	○	●	○
Jones-Oliveira Shell	○	○	○	○	○	○	●

Table 2

Overview of empirical benchmarks

	Replicate	Scatter Quantified	1D Spherical	1D Cartesian	1D Cylindrical	2D Cartesian	2D Axisymmetric	3D Cartesian
UNDEX Similitude	●	●	●	○	○	○	○	○
Spark-Generated Bubbles	●	○	●	○	○	○	●	●
SRI Spherical Sand Shock	●	○	●	○	○	○	○	○
Snay/Goertner Bubble	○	○	○	○	○	○	○	●
SAMSI	○	○	○	○	○	○	●	○
WEAG Dome	○	○	○	○	○	○	●	●
Seneca Lake Flat Plate	●	○	○	○	○	○	●	●
SBSI	○	○	○	○	○	○	○	●
Pipe Whip	○	○	○	○	○	○	○	●
Dynaflow Water Slug	○	○	○	○	○	○	○	●
IFM	○	○	○	○	○	○	○	●
IED	●	○	○	○	○	○	○	●
Oxygen Tank	○	○	○	○	○	○	○	●
ONR Cylinder	○	○	○	○	○	○	○	●
Jumbino	○	○	○	○	○	○	●	○
EBT	○	○	○	○	○	○	●	●
HTE	○	○	○	○	○	○	○	●
DDUS	○	○	○	○	○	○	○	●
Compliant Surface Bubble	○	○	○	○	○	○	●	○
GHBC	○	○	○	○	○	○	●	○
DRES 25cm Plate	○	○	○	○	○	○	●	○

ary/initial conditions. In practice, they are often approximations to the solution, since for realistic problems some sort of discretization is employed. Discretization of space and time, for example, results in simple solutions that are pieced together to approximate a continuous solution. Examples of this approach include the finite element, finite difference, and finite volume methods, as well as the method of characteristics. An alternative approach is to discretize the solution into a series that represents "response modes", a finite number of which are employed to approximate the solution. An analytical benchmark that employs the discretization process is most useful if a converged solution has been obtained. Unconverged analytical benchmarks are included in this compilation, but should be considered less reliable than the converged analytical benchmarks. If convergence has been demonstrated, analytical benchmarks are particularly suitable for the validation of computational models, since an "error measure" can be employed [5–8].

Analytical continuum dynamics benchmarks

- Shock Tube is a 1D cartesian Riemann Solution of shock and rarefaction (expansion) wave propagation resulting from interaction of two fluids initially at rest. APRICOT [9] is such a solution.
- Rayleigh–Plesset [10] is a 1D spherical solution for incompressible liquid bubble dynamics.
- Primakoff [11] is a 1D spherical solution of shock wave propagation in a water-like material due to the presence of a moving boundary.
- Cavitated Water Impact [12] is a 1D cartesian solution of the impact of cavitated water on a rigid boundary.
- P-alpha Shock Tube [13] is a Riemann Solution of shock and rarefaction (expansion) wave propagation resulting from interaction of two states of a porous solid (modeled with the P-alpha equation of state) initially at rest.
- Wardlaw/Mair Bubble [14,15] is a set of converged 1D spherical computational fluid dynamics solutions of underwater explosion bubble dynamics for various initial conditions and solution methods.

Table 3

Continuum dynamics benchmarks

	Analytical/Empirical	Water	Bubbly/Cavitating Water	Idealized Sediment	In-Situ Sediment	Air	Explosive
Shock Tube	A	●	○	○	○	○	○
Rayleigh-Plesset Solution	A	●	○	○	○	○	○
Primakoff Solution	A	●	○	○	○	○	○
Cavitated Water Impact	A	○	●	○	○	○	○
P-alpha Shock Tube	A	○	○	●	○	○	○
Wardlaw/Mair Bubble	A	●	○	○	○	○	○
UNDEX Similitude	E	●	○	○	○	○	○
Spark-Generated Bubbles	E	●	○	○	○	○	○
SRI Spherical Sand Shock	E	○	○	●	○	○	○
Snay/Goertner Bubble	E	●	○	○	○	○	○

Table 4

Structure/medium interaction benchmarks

	Analytical/Empirical	Plate/Shell	Welds	Bolts	Water	Bubbly/Cavitating Water	Idealized Sediment	In-Situ Sediment	Air	Explosive
Taylor Plate	A	●	○	○	●	○	○	○	○	○
Schechter/Bort Plates	A	●	○	○	●	○	○	○	○	○
Snay/Christian Plate	A	●	○	○	●	○	○	○	○	○
Bleich/Sandler Plate	A	●	○	○	●	○	○	○	○	○
Huang Plate	A	●	○	○	●	○	○	○	○	○
Murray Cylinder	A	●	○	○	●	○	○	○	○	○
Huang Sphere	A	●	○	○	●	○	○	○	○	○
Huang Concentric Spheres	A	●	○	○	●	○	○	○	○	○
Huang Cylinder	A	●	○	○	●	○	○	○	○	○
Huang Concentric Cylinders	A	●	○	○	●	○	○	○	○	○
Zhang/Geers Sphere	A	●	○	○	●	○	○	○	○	○
Jones-Oliveira Shell	A	●	○	○	●	○	○	○	○	○
SAMSI	E	○	○	○	○	○	●	○	○	○
WEAG Dome	E	●	○	○	●	○	○	○	○	○
Seneca Lake Flat Plate	E	○	○	○	●	○	○	○	○	○
SBSI	E	●	○	○	●	○	○	○	○	○
Pipe Whip	E	●	○	○	●	○	○	○	○	○
Dynaflow Water Slug	E	○	○	○	○	○	○	○	●	○
IFM	E	●	●	●	●	○	○	○	○	○
IED	E	●	●	○	●	○	○	○	○	○
Oxygen Tank	E	●	●	○	●	○	○	○	○	○
ONR Cylinder	E	●	○	○	●	○	○	○	○	○
Jumbino	E	●	○	○	●	○	○	○	○	○
EBT	E	●	●	●	○	○	○	○	●	○
HTE	E	●	●	○	●	○	○	○	○	○
DDUS	E	●	●	○	●	○	○	○	○	○
Compliant Surface Bubble	E	●	○	○	●	○	○	○	○	○
GHBC	E	●	○	○	●	○	○	○	○	○
DRES 25cm Plate	E	●	○	○	●	○	○	○	○	○

Analytical structure/medium interaction benchmarks

- Taylor Plate [16] is a 1D cartesian analytical solution of weak shock interaction with an air-backed plate; the water is modeled as a linear fluid with no allowance for cavitation, so an exact solution is obtained.
- Schechter/Bort Plates [17] is a 1D cartesian analytical solution of weak shock interaction with fluid-coupled plates, with the second plate either air-backed or water-backed; the water is modeled as a linear fluid with no allowance for cavitation, so an exact solution is obtained.
- Snay/Christian Plate [18] is a 1D cartesian analytical solution of strong shock interaction with an air-backed plate; the water is modeled as a nonlinear fluid with no allowance for cavitation. The solution is obtained using the method of characteristics.
- Bleich/Sandler Plate [19] is a 1D cartesian analytical solution that captures the occurrence of cavitation in water due to weak shock interaction with an air-backed plate; the water is modeled as a bilinear fluid. The solution is obtained using the method of characteristics.
- Huang Plate [20] is a 2D axisymmetric analytical solution of weak spherical shock interaction with an air-backed plate with no allowance for cavitation.
- Murray Cylinder [21] is a 2D cartesian analytical solution to the rigid body translational response of a cylinder to a plane underwater shock wave.
- Huang Sphere [22–24] is a 2D axisymmetric solution of the elastic response of submerged structures to weak shock waves. A fully converged solution has recently been obtained [24] that differs little from the previously obtained solution.
- Huang Concentric Spheres [25] is a 2D axisymmetric solution of the elastic response of submerged structures to weak shock waves.
- Huang Cylinder [26,27] is a 2D and 3D cartesian solution of the elastic response of submerged structures to weak shock waves.
- Huang Concentric Cylinders [28] is a 2D cartesian solution of the elastic response of submerged structures to weak shock waves.

- Zhang/Geers Sphere [29–31] is a 2D axisymmetric solution of the elastic response of a fluid-filled sphere to weak water shock waves.
- Jones-Oliveira Shell [32,33] is a 3D solution of the elastic response of a submerged prolate spheroidal shell to weak shock waves.

2.2. *Empirical benchmarks*

Empirical benchmarks, listed in Table 2, are based upon experiments. They may represent a single experiment or multiple experiments. They are most valuable when presented with statistical information quantifying the means and spreads of the measurements. Empirical benchmarks are far more valuable if accuracy of the data has been established; unfortunately, this issue is not addressed in any of the examples.

Empirical Continuum Dynamics Benchmarks

- UNDEX Similitude [34] is a spherical 1D compilation of many UNDEX experiments, from which performance parameters are derived for various explosives. Additionally, the scatter in the experimental data has been statistically quantified.
- Spark-Generated Bubbles [35–41] are bubbles generated by sparks in water, for the purpose of simulating underwater explosions.
- SRI Spherical Sand Shock [42] is a spherical 1D set of experiments of detonation in sand in various states of saturation.
- Snay/Goertner Bubble [43] experiments are underwater explosion bubbles influenced by a nearby, rigid cylinder.

Empirical structure/medium interaction benchmarks

- SAMSI (Sand and Mine Structure Interaction) [44,45] experiments are thick-walled cylinders with a flat, air-backed end plate subjected to axisymmetric sediment shock loading.
- WEAG (Western European Armaments Group) Dome [46] is a domed, air-backed structure subjected to underwater shock and bubble jetting loading from above (gravity vector is aligned with the structural axis of symmetry); the 2D version is unstiffened, while the 3D version is asymmetrically stiffened.
- Seneca Lake Flat Plate experiments [47,48] are flat, circular, horizontally placed, water-backed plate subjected to underwater shock and bubble collapse loading from below (gravity vector is aligned with the structural axis of symmetry). The axisymmetric experiments were conducted in the NSWC Hydrotank in Silver Spring in Maryland, and the 3D (asymmetrically stiffened) experiments were conducted at Seneca Lake in New York State.
- SBSI (Schmidt Bubble/Structure Interaction) experiments [49] are rectangular, vertically placed, water backed plates subjected to shock and bubble collapse loading from the side (gravity vector is not aligned to the charge/plate axis).
- Pipe Whip [50] experiments are cylinders (with a stiffened test section) subjected to shock and bubble pulse loading resulting in whipping response.
- Dynaflow Water Slug [51] experiments are slugs of water fired at flexible rectangular plates.
- IFM (Internal Fluid Model) [52] experiments are concentric cylinders, with water entrained between the inner and outer cylinders, subjected to large standoff water shock loading. A preliminary test was conducted on a single cylinder.
- IED (Independent Exploratory Development) [53] experiments are unstiffened cylinders subjected to small standoff water shock loading.
- Oxygen Tank [54] experiments are externally stiffened cylinders subjected to large standoff water shock loading.
- ONR Cylinder [55] experiments are cylinders subjected to large standoff water shock loading.
- Jumbino [56] experiments are thick-walled, water-filled axisymmetric structures subjected to internal blast.
- EBT (Explosion Bulge Test) [57] is a class of experiments in which thick circular plates with welds are subjected to explosion loading in air.
- HTE (Hull Toughness Element) [58] is a class of experiments in which thick, welded, precracked plates are subjected to underwater explosion loading.
- DDUS (Deep Depth UNDEX Simulator) [59] experiments are a set of experiments in which stiffened cylinders, housed within a pressurized outer chamber to simulate deep depth, are subjected to large-standoff water shock loading.
- Compliant Surface Bubble [60] is a 2D axisymmetric set of experiments of bubble collapse onto a compliant surface composed of rubber materials.
- GHBC (Guirguis Hydro-Bulged Cylinder) [61, 62] is a 2D axisymmetric set of experiments of water-filled structures subjected to internal blast.
- DRES (Defence Research Establishment, Suffield) 25 cm Plate [63] is a series of 2D axisymmetric experiments of bubble interaction with a circular metal plate.

3. Benchmark computations

Benchmark computations, compiled in Table 5, are organized by both code and benchmark. Precautions in evaluating validation computations are also outlined.

3.1. Benchmark computations organized by code

Codes are grouped into three categories: Doubly Asymptotic Approximation (DAA) codes, hydrocodes, and other types of approaches.

Benchmark computations employing DAA codes

DAA codes are structural dynamics codes employing the Doubly Asymptotic Approximation (DAA) [64–66], a robust structure–medium interaction (SMI) approximation that is asymptotically exact in both the low-frequency and high-frequency limits. In finite-element response calculations, it provides a set of ordinary differential equations (ODEs) for the SMI that are solved in tandem with the response ODEs for the dry structure. The inputs for a typical UNDEX calculation are the incident-wave pressure and velocity fields, i.e., those that would exist in the absence of the structure.

- The ADINA-S special-purpose shock/structure interaction code [67,68], in which an implementation of the DAA provides the fluid/structure interaction loads for the ADINA structural dynamics code, was exercised on a Huang Sphere model [67], Huang Cylinder model [68], and Huang Concentric Cylinders model [68].
- The DYNA/FSI special-purpose shock/structure interaction code [69], in which an implementation of the DAA provides the fluid/structure interaction loads for the DYNA3D hydrocode, was exercised on a Bleich/Sandler Plate model [69], and Huang Sphere model [70,71].
- The ELSHOK special-purpose shock/structure interaction code [72–74], in which an implementation of the DAA provides the fluid/structure interaction loads for the elastic structural dynamics code, was exercised on an ONR Cylinder model [75–77].
- The EPSA special-purpose shock/structure interaction code [78–83], in which an implementation of the DAA provides the fluid/structure interaction loads for the elastic-plastic structural dynamics code, was exercised on a Huang Sphere model [83–85], Huang Concentric Spheres model [83–85], IFM model [83,86–88], and DDUS model [89]. EPSA has recently been coupled to the FUSE Total Lagrangian hydrocode.
- The USA-ABAQUS special-purpose shock/structure interaction code [90], in which the USA (Underwater Shock Analysis) code implementation of the DAA provides the fluid/structure interaction loads for the ABAQUS structural dynamics code, was exercised on a Huang Sphere model [90].
- The USA/NASTRAN special-purpose shock/structure interaction code [91], in which the USA (Underwater Shock Analysis) code implementation of the DAA provides the fluid/structure interaction loads for the NASTRAN structural dynamics code, was exercised on a Huang Concentric Spheres model [92], an ONR Cylinder model [93], and a Bleich–Sandler Plate model [94].
- The USA-STAGS-CFA special-purpose shock/structure interaction code [95], in which the USA (Underwater Shock Analysis) code implementation of the DAA, and the CFA (Cavitating Fluid Analyzer) code, provide the fluid/structure interaction loads for the STAGS structural dynamics code, was exercised on a Schechter/Bort Plates model [96], Bleich/Sandler Plate model [97], Huang Sphere model [98], Huang Cylinder model [98–100], Huang Concentric Cylinders model [96,101,102], and ONR Cylinder model [103].
- The USA-VEC/DYNA3D special-purpose shock/structure interaction code, in which the USA (Underwater Shock Analysis) code implementation of the DAA provides the fluid/structure interaction loads for the VEC/DYNA3D hydrocode, was exercised on an IFM model [86]. This capability is also available for the commercial version, LS-DYNA.

Benchmark computations employing hydrocodes

"Hydrocodes" are computational mechanics codes capable of simulating wave propagation phenomena in both solids and fluids. As such, they are to be distinguished from computational fluid dynamics (CFD) codes, which are *hydrodynamics* or aerodynamics codes.

- The ALE3D multimaterial Arbitrary Lagrangian Eulerian (ALE) hydrocode [104] was compared with UNDEX Similitude [108], and exercised on a Seneca Lake Flat Plate model [105], Snay/Goertner Bubble model [105], Pipe Whip model [105], and IED Cylinder model [105].
- The coupling of the CTH Eulerian hydrocode with the EPIC Lagrangian hydrocode through the

Table 5
Compilation of benchmark computations

		DAA Codes								Hydrocodes								Other			
	Analytical/Empirical	ADINA-S	DYNA/FSI	ELSHOK	EPSA	USA-ABAQUS	USA-NASTRAN	USA-STAGS-CFA	USA-VEC/DYNA	ALE3D	CTH-EPIC	DYNA3D	DYSMAS/ELC	EPIC	LS-DYNA	MSC/DYTRAN	PRONTO/SPH	DynaFS-NIKE	CFDLIB-PRONTO	CTH-DYNA3D Link	IFSAS-VAST
Shock Tube	A										●		●								
Rayleigh-Plesset Solution	A																	●			
Primakoff Solution	A																				
Cavitated Water Impact	A												●								
P-alpha Shock Tube	A												●								
Wardlaw/Mair Bubble	A																				
Taylor Plate	A																				
Schechter/Bort Plates	A							●													
Snay/Christian Plate	A																				
Bleich/Sandler Plate	A		●					●													
Huang Plate	A													●							
Murray Cylinder	A																				
Huang Cylinder	A	●						●								●					
Huang Concentric Cylinders	A	●						●													
Huang Sphere	A		●		●	●		●						●		●	●				
Huang Concentric Spheres	A				●		●														
Zhang/Geers Sphere	A																				
Jones-Oliveira Shell	A																				
UNDEX Similitude	E									●			●	●	●	●		●			
Spark-Generated Bubbles	E																	●			
SRI Spherical Sand Shock	E										●		●								
Snay/Goertner Bubble	E									●								●			
SAMSI	E										●		●								
WEAG Dome	E												●								
Seneca Lake Flat Plate	E									●			●				●	●			
SBSI	E																				
Pipe Whip	E									●											
Dynaflow Water Slug	E																				
IFM	E				●				●			●									
IED	E									●			●			●	●			●	
Oxygen Tank	E												●								
ONR Cylinder	E			●			●	●													
Jumbino	E																		●		
EBT	E													●							
HTE	E																				
DDUS	E				●																
Compliant Surface Bubble	E																				
GHBC	E												●								
DRES 25cm Plate	E																				●

ZAPOTEC module [106,107] was exercised on a SAMSI model [13]; CTH, in standalone mode, was compared with UNDEX Similitude [108], and exercised on an SRI Spherical Sand Shock model [13].

- The DYNA3D Lagrangian hydrocode [109] was exercised on an IFM model [86].
- The DYSMAS/ELC Coupled Eulerian/Lagrangian (CEL) hydrocode [110] was exercised on a SAMSI model [44,45], WEAG Dome model [46],

Seneca Lake Flat Plate model [111,112], IED model [113], Oxygen Tank model [54], and a GHBC model [114]. DYSMAS/E, in stand-alone mode, was exercised on Shock Tube problems (including Apricot #1) [115,116], a Cavitated Water Impact model [117], SRI Spherical Sand Shock model [13], P-alpha Shock Tube model [13], and was compared with UNDEX Similitude [113].

- The EPIC hydrocode [118] was compared with UNDEX Similitude [119], and exercised on a Huang Plate model [120], Huang Sphere model [120], and an EBT model [121].
- The LS-DYNA Lagrangian hydrocode [122,123] was exercised on an UNDEX Similitude model [108].
- The MSC/DYTRAN Coupled Eulerian/Lagrangian (CEL) and Arbitrary Lagrangian/Eulerian (ALE) hydrocode [124,125] was compared with UNDEX Similitude [126], and exercised on a Huang Sphere model [126,127], Huang Cylinder model [126,127], and an IED Cylinder model [128].
- The PRONTO/SPH Lagrangian hydrocode with a Smoothed Particle Hydrodynamics (SPH) option [129] was exercised on a Huang Sphere model [130], IED Cylinder model [130], and Seneca Lake Flat Plate model [130].

Benchmark computations employing other codes

Other code types include uncoupled approaches, and traditional Computational Fluid Dynamics (CFD) codes coupled to structural response codes. CFD codes include Boundary Element Method (BEM) codes, which treat the fluid as incompressible and irrotational, allowing discretization of material interfaces only. CFD codes are also common in Eulerian or Arbitrary Lagrangian/Eulerian (ALE) formulations.

- The 2DynaFS special-purpose bubble/structure interaction code coupled to the NIKE2D structural dynamics code [131,132] was exercised on a Seneca Lake Flat Plate model [133]. 2DynaFS and 3DynaFS, in stand-alone mode, have been exercised on a Rayleigh–Plesset Solution model [134], Snay/Goertner Bubble model [134–138], a Spark-Generated Bubbles model [138], a Seneca Lake Flat Plate model [132], and compared with UNDEX similitude [134].
- The CFDLIB family of fluid dynamics codes coupled to the PRONTO2D hydrocode [139–141] was exercised on a Jumbino model [56].
- The CTH-DYNA3D Link [142] is an uncoupled transfer of information from a CTH hydrocode model to a DYNA3D hydrocode model. It was exercised on an IED model [142].
- The BUB3D incompressible Eulerian fluid dynamics code [143] is not coupled to a structural dynamics code, but can prescribe the motion of a boundary. It was exercised on a Seneca Lake Flat Plate model [144] and a Snay/Goertner Bubble model [144].
- The IFSAS compressible CFD code [145] coupled to the VAST structural dynamics code was exercised on a DRES 25 cm Plate model [146].

3.2. *Benchmark computations organized by benchmark*

Analytical benchmark computations

- Shock Tube simulations include DYSMAS/E models [115,116], including Apricot #1 [115].
- Rayleigh–Plesset Solution [10] simulations include a 2DynaFS model [134].
- Cavitated Water Impact [12] simulations include a DYSMAS/E model [117].
- P-alpha Shock Tube [13] simulations include a DYSMAS/E model [13].
- Schechter/Bort Plates [17] simulations include a USA-STAGS-CFA model [96].
- Bleich/Sandler Plate [19] simulations include a USA-STAGS-CFA model [97], a USA -NASTRAN-CFA model [94], and a DYNA/FSI model [69].
- Huang Plate [20] simulations include an EPIC model [120].
- Huang Sphere [22–24] simulations include an MSC/DYTRAN model [126,127], an EPSA model [83–85], a USA-STAGS-CFA model [98], a DYNA/FSI model [70,71], an EPIC model [119], a PRONTO/SPH model [130], and a USA-ABAQUS model [90].
- Huang Concentric Spheres [25] simulations include an EPSA model [78,83,84], and a USA-NASTRAN model [92].
- Huang Cylinder [26,27] simulations include an MSC/DYTRAN model [126,127], a USA -STAGS- CFA model [98–100], and an ADINA-S model [67].
- Huang Concentric Cylinders [28] simulations include an ADINA-S model [67], and USA -STAGS-CFA models [96,101,102].

Empirical benchmark computations

- UNDEX Similitude [34] simulations include a DYSMAS/ELC model [113], a CTH model [108], an MSC/DYTAN model [126], an ALE3D model [108], an EPIC model [119], an LS-DYNA model [108], and a 2DynaFS model [134].
- Spark-Generated Bubbles [35] simulations include a 3DynaFS model [138].
- SRI Spherical Sand Shock [42] simulations include a DYSMAS/ELC model [13], and a CTH-EPIC model [13].
- Snay/Goertner Bubble [43] simulations include a 3DynaFS model [134–138], and an ALE3D model [105].
- SAMSI (Sand and Mine Structure Interaction) [44] simulations include a DYSMAS/ELC model [13] and a CTH-EPIC model [13].
- WEAG (Western European Armaments Group) Dome [46] simulations include a DYSMAS/ELC model [46].
- Seneca Lake Flat Plate [47,48] simulations include a DYSMAS/ELC model [111,112], a 2DynaFS-NIKE2D model [133], an ALE3D model [105], and a PRONTO/SPH model [130].
- Pipe Whip [50] simulations include an ALE3D model [105].
- IFM (Internal Fluid Model) [52] simulations include an EPSA model [86–88], a USA-VEC/DYNA model [86], and a DYNA3D model [86].
- IED (Independent Exploratory Development) [53] simulations include a DYSMAS/ELC model [113], an MSC/DYTRAN model [128], an ALE3D model [105], a PRONTO/SPH model [130], and a CTH-DYNA3D Link model [142].
- Oxygen Tank [54] simulations include a DYSMAS/ELC model [54].
- ONR Cylinder simulations include an ELSHOK model [75–77], a USA-NASTRAN model [93], and a USA-STAGS-CFA model [103].
- Jumbino [56] simulations include a CFDLIB-PRONTO2D model [56].
- EBT (Explosion Bulge Test) [57] simulations include an EPIC model [121].
- DDUS (Deep Depth UNDEX Simulator) [59] simulations include an EPSA model [89].
- GHBC [61,62] simulations include a DYSMAS/ELC model [114].
- DRES 25 cm Plate [63] simulations include an IFSAS-VAST model [146].

3.3. *Caveat emptor*

Existence and documentation of a benchmark computation does not imply that a code was validated, or even that the model results were "good". For example, faulty results have been published:

- The original Huang Sphere publication [22] includes a slight error, as pointed out in [66], and corrected in [24].
- An EPSA model [83–85] of the Huang Sphere analytical benchmark [22] predicts large-amplitude, high-frequency oscillations superimposed on the fundamental response, theorized by the authors to be "real" since convergence had not been demonstrated in the Huang Sphere analytical solution. A more recent analysis [24] of the analytical benchmark, in which convergence was obtained, revealed that the large-amplitude, high-frequency oscillations predicted by the EPSA model were in error.
- A DYNA3D model of the IFM empirical benchmark [86] included a bug, resulting in some incorrect data generated. The faulty data were published, along with a note in the document indicating the presence of the bug. The faulty computational data were due to the computational model, not the DYNA3D code.
- A report describing a DYTRAN model of the IED Cylinder empirical benchmark [128] compares the simulated maximum deflection of the cylinder to the final deflection measured in the experiment. More recent analyses with DYSMAS/ELC [113] and ALE3D [105] show that significant elastic rebound is present, and that the agreement between the DYTRAN model results and experimental data was fortuitous.

In general, disagreement between computational model results and benchmark data does not imply a faulty code or even a faulty model; many sources of error exist in the generation of both computational and experimental data. Limitations on gauges and data reduction, and unknown response aspects (lack of material characterization, effects of welds, bolts, fixtures, etc.), are examples of issues that can significantly influence the value of experimental data. Modeling approximations and errors, and lack of discretization convergence, are examples of issues that can significantly influence the accuracy, and therefore the value, of computational data.

Alternately, computational models can be so complex that results seeming to validate a model may be fortuitous. So many options are available in computational mechanics codes that offsetting errors should be expected.

This compilation of benchmarks is not complete; some of the codes have been extensively exercised on “classified” benchmarks, or on more complex empirical data that are not usually considered “benchmarks”.

4. Summary

In the interest of initiating a dialog within the UNDEX community on validation techniques, a limited set of UNDEX benchmarks, and computations thereof, is presented. Extension of this database beyond the response of submerged structures to underwater explosions is proposed; natural extensions include the response of internal equipment and floating structures, as well as hydrodynamic ram problems.

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