A REVIEW FOR BENCHMARK EXPERIMENTS FOR VALIDATION OF PERIDYNAMIC MODELS

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MOTIVATION

Adequacy of peridynamic models and simulations

One important key for the adequacy of a model is the confidence how it compares with experimental data [27, 28].

Main objectives

- Review the available experimental data
- Provide an measurement for the confidence level
- Advanced visualization techniques for additional comparison against experiments

OUTLINE

❶ METHODOLOGY

- Collection of data
- Metric for the comparison

❷ COMPARISON AGAINST EXPERIMENTS

- Wave propagation
- Crack initiation/propagation
  - Composite
  - Steel/Aluminum
  - Concrete
  - Glass
  - Various

❸ CONFIDENCE OF PERIDYNAMICS MODELS AND SIMULATIONS

- Scalar observable
- Series of obversable

❹ ADVANCED VISUALIZATION TECHNIQUES

- Physically-based rendering
- Extraction of additional attributes

❺ CONCLUSION AND OUTLOOK

COLLECTION OF DATA

Search in Web of Science[1] for

Comparison against experiments

- *peridynamics* + *experiment*
- *peridynamics* + *benchmark*
- 39 papers including comparison against experimental data
- Using 52 experimental paper

Advanced visualization techniques

- *peridynamics* + *computer graphics*
- *peridynamics* + *visualization*
- 5 papers (2 physically-based rendering and 3 for the extraction)
- Using 1 experimental paper

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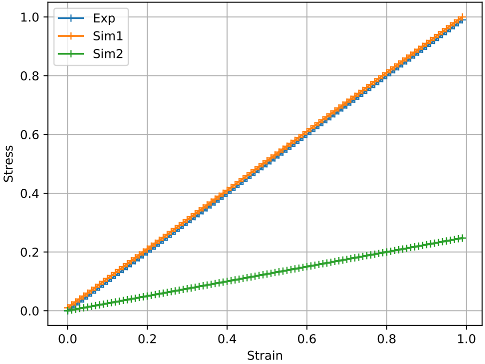
[1] https://webofknowledge.com/

METRIC FOR COMPARISON OF EXPERIMENTAL DATA



$R^2 \in [0,1]$ **correlation**

- Obtain y-values from simulation and y-values from experiment at same x-values
- Do linear regression with y-values
- Use r value squared as confidence level

COMPARISON OF WAVE PROPAGATION AGAINST EXPERIMENTS

Application	B	S	Material	Exp
Stress wave propagation (half-plane)	✓		Plastic polymer (CR-39)	[20]
Wave speed (Edge-on impact experiment)	✓		ALON,PMMA	[76, 75, 74]
Split-Hopkinson pressure bar	✓		Aluminum	[17, 10]
Wave dispersion and propagation		✓	Sandstone	[82, 89]

Table 1: Applications for the comparison of wave propagation against experimental resuls. **Legend**: **B** refers to bond-based peridynamics, **S** refers to state-based peridynamics, **Exp** to experimental data, and **Sim** to simulation.

COMPOSITE

Application	B	S	Material	Exp	Sim
Interaction between a dynamically growing crack	✓		Composite	[53]	[2]
Damage growth prediction (Six-bolt specimen)	✓		Composite	[73]	[64]
Damage prediction (Center-cracked laminates)	✓		Composite	[4, 48, 83, 8]	[49]
Dynamic tension test (prenoteched rectangular plate)	✓		Composite	[43, 8]	[39]

Table 2: Applications of bond-based and state-based peridynamics for the comparison with experimental data. **Legend**: **B** refers to bond-based peridynamics, **S** refers to state-based peridynamics, **Exp** to experimental data, and **Sim** to simulation.

Remarks

- Only quantitative comparison against experiment was done, e.g. crack pattern or crack branches.
- Only bond-based peridynamic models were applied.

STEEL/ALUMINUM

Application	B	S	Material	Exp	Sim
Crack growth (Kalthoff-Winkler)	✓	✓	Steel	[45, 47, 46]	[71, 3, 36, 90]
Dynamic fracture		✓	Steel (4340)	[32]	[31]
Fracture (Compact tension test)	✓		Aluminum,Steel	[59, 61, 7, 54]	[84, 88, 87]
Taylor impact test		✓	Aluminum	[16, 44]	[29, 30, 3]
Ballistic impact test		✓	Aluminum (6061-T6)	[81]	[79]

Table 3: Applications of bond-based and state-based peridynamics for the comparison with experimental data. **Legend**: **B** refers to bond-based peridynamics, **S** refers to state-based peridynamics, **Exp** to experimental data, and **Sim** to simulation.

CONCRETE

Application	B	S	Material	Exp	Sim
Lap-splice experiment	✓		Concrete	[33]	[33]
3-point bending beam	✓	✓	Concrete	[41, 14]	[35, 5]
Failure in a Barazilian disk under compression		✓	Concrete	[35]	[38]

Table 4: Applications of bond-based and state-based peridynamics for the comparison with experimental data. **Legend**: **B** refers to bond-based peridynamics, **S** refers to state-based peridynamics, **Exp** to experimental data, and **Sim** to simulation.

GLASS

Application	B	S	Material	Exp	Sim
Dynamic crack propagation (prenotched thin plate)	✓		Glass	[11, 24, 67]	[90, 37, 2]
Impact damage with a thin polycarbonate backing	✓		Glass	[26, 15, 6]	[40]
Single crack paths (quenched glass plate)	✓		Glass	[86, 69, 9]	[50]
Multiple crack paths (quenched glass plate)	✓		Glass	[70, 85]	[50]
Crack tip propagation speed	✓		Glass	[11]	[36, 90, 37]
Fast cracks in PMMA	✓		PMMA	[25]	[2]
Tensile test	✓		PMMA	[77]	[21]

Table 5: Applications of bond-based and state-based peridynamics for the comparison with experimental data. **Legend**: **B** refers to bond-based peridynamics, **S** refers to state-based peridynamics, **Exp** to experimental data, and **Sim** to simulation.

Remarks

- Six papers comapred against the same experimental results: FP Bowden et al. “Controlled fracture of brittle solids and interruption of electrical current”. In: *Nature* 216.5110 (1967), pp. 38–42.
- Only bond-based peridynamics was considered.

VARIOUS

Application	B	S	Material	Exp	Sim
Ruptures in Bio membranes		✓	Bio membranes	[34]	[78]
Arctic engineering		✓	Ice	[72]	[57]
Electronic packages	✓		Graphene	[63]	[65]
Dynamic crack propagation	✓		FGM (Epoxy/Soda-lime glass)	[51, 1, 52]	[19]

Table 6: Applications of bond-based and state-based peridynamics for the comparison with experimental data. **Legend**: **B** refers to bond-based peridynamics, **S** refers to state-based peridynamics, **Exp** to experimental data, and **Sim** to simulation.

Remarks

- For arctic engineering three different speeds of the drill were compared.
- Confidence level heavily depends on the speed value.

RELATIVE ERROR FOR SCALAR OBSERVABLE

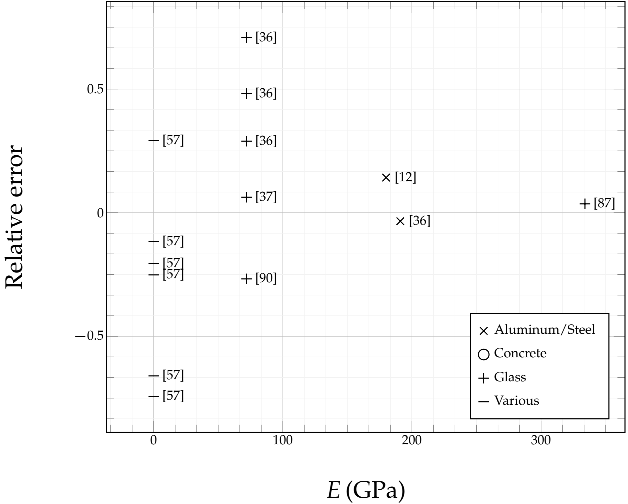


Figure 1: The plot shows the relation between the Young modulus E of the material and the relative error of the experimental result and the obtained observable in the simulation.

Table

OVERVIEW RELATIVE ERROR

Application	Material	Observable	Rel. error	Exp	Sim
Edge-on impact experiment	ALON	Avg. propagation speed of primary wave front	$3.57 \cdot 10^{-2}$	[60]	[87]
Kalthoff-Winkler experiment	Steel	Crack initiation time	$-3.45 \cdot 10^{-2}$	[58]	[36]
Kalthoff-Winkler experiment	Steel	Crack propagation speed	0.14	[45, 68]	[12]
Crushing-brittle ice by a rotating cylinder	Ice	Mean force at $50\,\mathrm{mm\,s^{-1}}$	-0.74	[72]	[57]
Crushing-brittle ice by a rotating cylinder	Ice	Mean force at $130\,\mathrm{mm\,s^{-1}}$	-0.21	[72]	[57]
Crushing-brittle ice by a rotating cylinder	Ice	Mean force at $210\,\mathrm{mm\,s^{-1}}$	-0.25	[72]	[57]
Crushing-brittle ice by a rotating cylinder	Ice	Peak force at $50\,\mathrm{mm\,s^{-1}}$	-0.66	[72]	[57]
Crushing-brittle ice by a rotating cylinder	Ice	Peak force at $130\,\mathrm{mm\,s^{-1}}$	-0.12	[72]	[57]
Crushing-brittle ice by a rotating cylinder	Ice	Peak force at $210\,\mathrm{mm\,s^{-1}}$	0.29	[72]	[57]
Pre-cracked glass (step tensile loading)	Soda-lime	Max. crack propagation speed	$6.27 \cdot 10^{-2}$	[11]	[37]
Pre-cracked plate (step tensile loading)	Soda-lime	Max. crack propagation speed	-0.27	[11]	[90]
Pre-cracked plate (step tensile loading)	Soda-lime	Max. crack propagation speed (16 281 nodes)	0.29	[11]	[36]
Pre-cracked plate (step tensile loading)	Soda-lime	Max. crack propagation speed (4141 nodes)	0.48	[11]	[36]
Pre-cracked plate (step tensile loading)	Soda-lime	Max. crack propagation speed (refined)	0.71	[11]	[36]

Table 7: Relative error between the observable measured in the experiment and obtained in the simulation.

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R^2 CORRELATION FOR SERIES OF OBSERVABLE

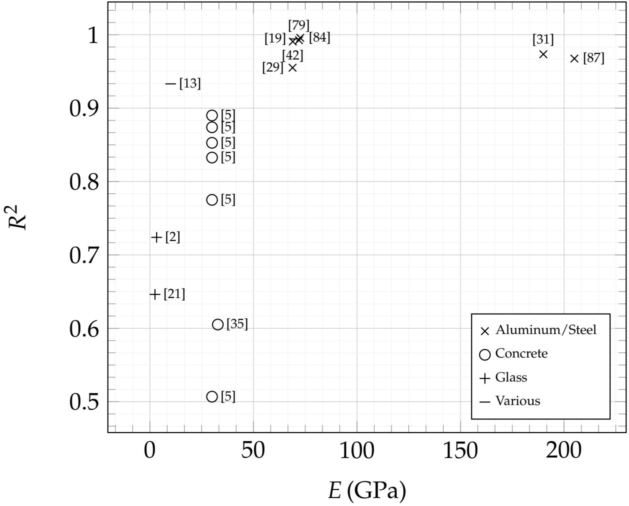

Figure 2: The plot shows the relation between the Young modulus E of the material and the extracted correlation R^2 of the experimental plot and the plot obtained by simulations.

Table

OVERVIEW R^2 CORRELATION

Application	Material	Observable	R^2	Exp	Sim
Split-Hopkinson pressure bar	Aluminum	Strain vs time	0.99	[17]	[42]
Taylor impact test	Aluminum (6061-T6)	Norm diameter/length; strain vs stress	0.96	[44, 16]	[29]
Ballistic impact test	Aluminum (6061-T6)	Residual vel vs impact vel	0.99	[81]	[79]
Dynamic fracture	Steel (4340)	Strain vs stress	0.97	[32]	[31]
Compact tension test	Aluminum (D16AT)	Force vs CMOD	1	[54, 80]	[84]
Compact tension test	SAE 1020 steel	Crack path position	0.97	[61]	[87]
3-point bending	Concrete	Load vs CMD	0.61	[41]	[35]
3-point bending (D3)	Concrete	Load vs CMOD	0.85	[14]	[5]
3-point bending (D6)	Concrete	Load vs CMOD	0.89	[14]	[5]
3-point bending (D9)	Concrete	Load vs CMOD	0.77	[14]	[5]
3-point bending (D3 LPD-load)	Concrete	Load vs LPD	0.87	[14]	[5]
3-point bending (D6 LPD-load)	Concrete	Load vs LPD	0.83	[14]	[5]
3-point bending (D9 LPD-load)	Concrete	Load vs LPD	0.51	[14]	[5]
Fast crack growth	PMMA	Crack velocity vs time	0.72	[25]	[2]
Tensile test	PMMA	Poisson ratio vs time	0.65	[77]	[21]
3-point loading	FEM (Epoxy/Soda-lime glass)	Crack length vs time	0.99	[52]	[19]
Wave dispersion and propagation	Sandstone	Dispersion curves	0.93	[82]	[13]

Table 8: R^2 correlation between the series of observables between experiment and simulation. **Abbreviations**: crack mouth displacement (CMD), crack mouth opening displacement (CMOD), and load point displacement (LPD).

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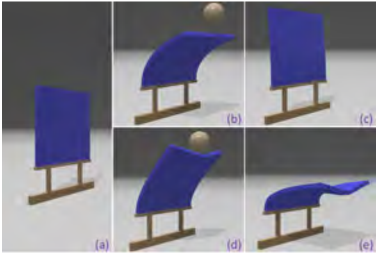
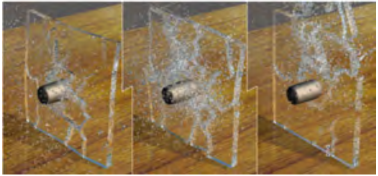
PHYSICALLY-BASED RENDERING



Wei Chen et al. "Peridynamics-Based Fracture Animation for Elastoplastic Solids". In: *Computer Graphics Forum* (2017), n/a–n/a. ISSN: 1467-8659



J. A. Levine et al. "A Peridynamic Perspective on Spring-mass Fracture". In: *Proceedings of the ACM SIGGRAPH/Eurographics Symposium on Computer Animation*. SCA '14. Copenhagen, Denmark: Eurographics Association, 2014, pp. 47–55

Methodology
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Extraction of additional attributes
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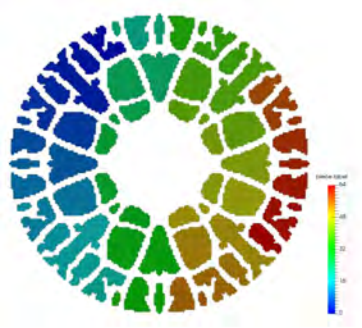
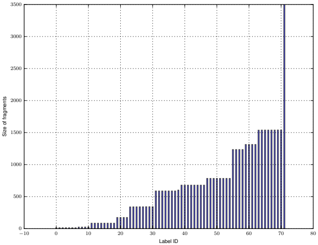
EXTRACTION OF FRAGMENTS





- David Littlewood, Stewart Silling, and Paul Demmie. "Identification of Fragments in a Meshfree Peridynamic Simulation". In: *ASME 2016 International Mechanical Engineering Congress and Exposition*. American Society of Mechanical Engineers. 2016, V009T12A071–V009T12A071
- Patrick Diehl et al. "Extraction of Fragments and Waves After Impact Damage in Particle-Based Simulations". In: *Meshfree Methods for Partial Differential Equations VIII*. Springer International Publishing, 2017, pp. 17–34

FRACTURE PROGRESSION

Setting	Growth velocity $\mathrm{m\,s^{-1}}$
Exp	1000
SPH	1200
PD	Mean: 1142, Median: 1144

Michael Bußler et al. “Visualization of fracture progression in peridynamics”. In: *Computers & Graphics* 67 (2017), pp. 45–57. ISSN: 0097-8493

SUMMARY

Application	B	S	Reference
Animation of brittle fracture	✓		[55]
Fracture animation in elastoplastic solids		✓	[18]
Waves after impact damage	✓		[23]
Fracture progression	✓	✓	[12]
Extraction of fragments	✓		[23, 56]

Table 9: Overview of applications of bond-based and state-based peridynamics in visualization of fracture in solids. **Legend**: *B* refers to bond-based peridynamics and *S* refers to state-based peridynamics.

Remarks

- All these advances techniques are additional models.
- Validation against experiments is needed for these models.

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