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The University of Texas at Austin

5pPA9: Time-varying elastic wave mode conversion in vibrating elastic beams with subwavelength nonlinearity

183rd Meeting of the Acoustical Society of America

09 December 2022

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Overview

Background and motivation

- Time-varying media
- Pump-probe evaluation techniques

Methodology

- Introduction of time-varying properties via defects

Applications

- Nondestructive evaluation
- Metamaterial design

Summary

Time-varying media

> "A medium whose properties vary with time over a relevant time scale."

For acoustic/elastic mediums, properties can be...

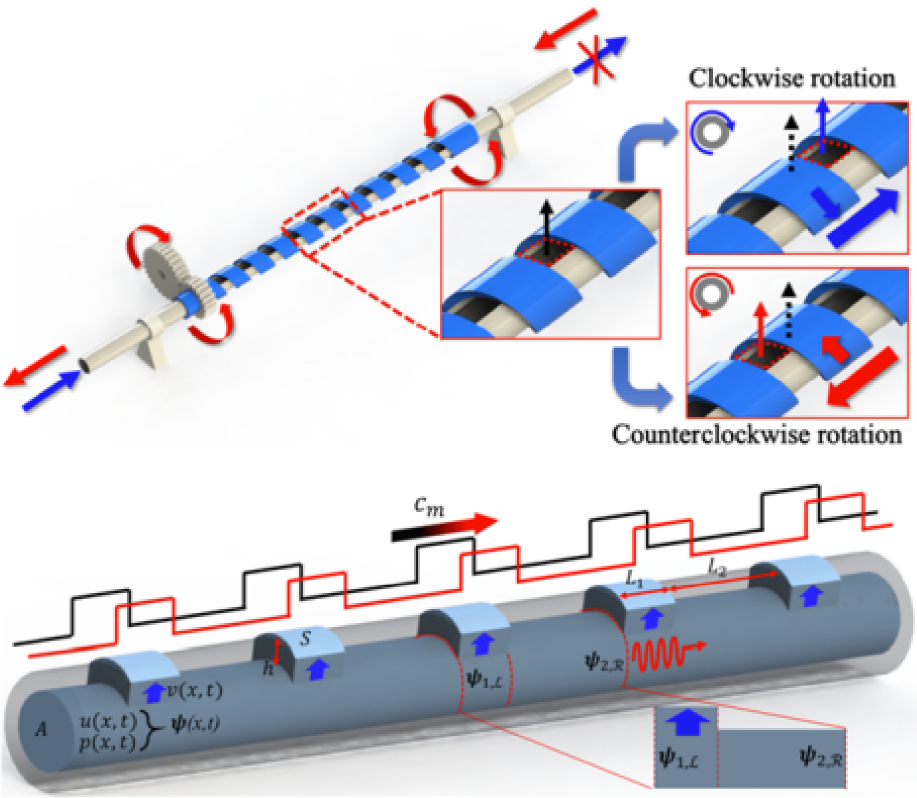
- **Material**: density, stiffness, nonlinearity
- **Non-material**: boundary conditions

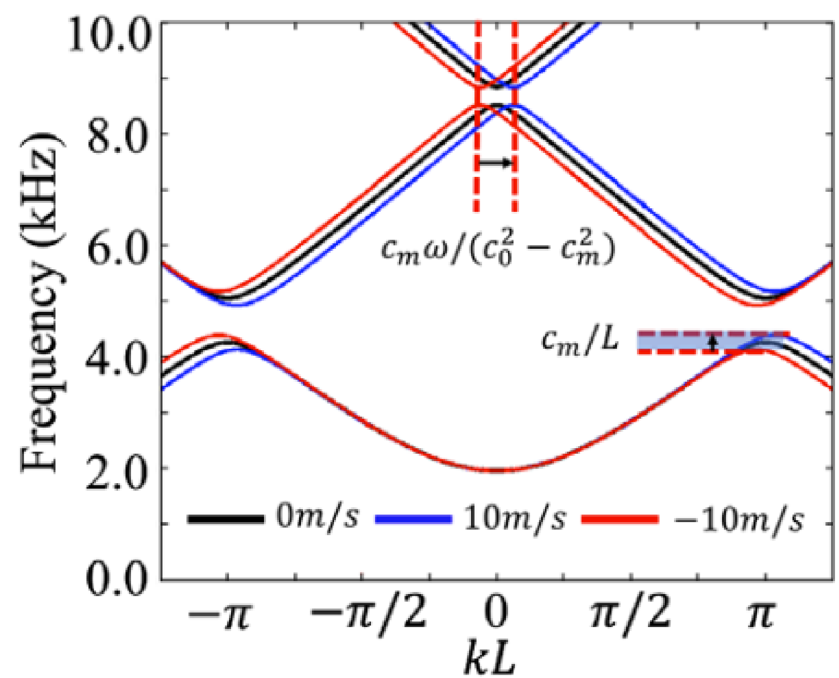
Variation can result in interesting and useful behavior

- Nonreciprocal transmission in waveguides
- Shifting of structural dynamic (SD) modes

Time-varying media

Ex: variation of boundary condition



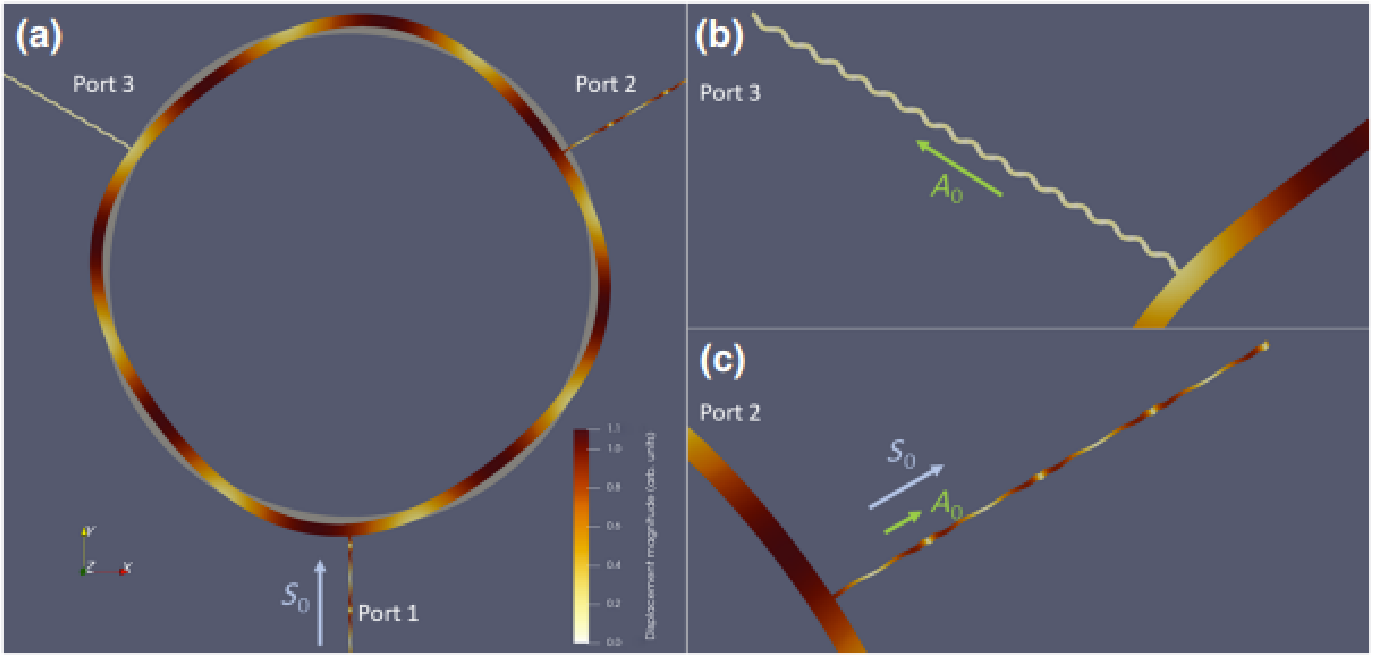


Spatiotemporal modulation of the boundary condition allows for breaking of reciprocity

[Xu et al. Physical Observation of a Robust Acoustic Pumping in Waveguides with Dynamic Boundary. *Phys. Rev. Lett.* (2021)]

Time-varying media

Ex: variation of material properties



Spatiotemporal modulation of the Young's modulus allows for nonreciprocity, mode conversion

[Goldsberry et al. Nonreciprocity and Mode Conversion in a Spatiotemporally Modulated Elastic Wave Circulator. *Phys. Rev. Appl.* (2022)]

Pump-probe techniques

Time-variation of media can be useful to NDE through **pump-probe techniques:**

A "pump" wave modulates the medium such that sensitive indicator parameters can be measured by a "probe" wave

Many exist, and can be application-specific

- Vibroacoustic modulation (VAM)
  - Aymerich and Staszewski (*SHM* 9(6), 2010)
- Dynamic acousto-elastic testing (DAET)
  - Rivière et al (*J. Appl. Phys.* 114(5), 2013)
- Resonant ultrasound spectroscopy (RUS)
  - Leisure and Willis (*J. Phys. Condens. Matter* 9(28), 1997)
- Nonlinear elastic wave spectroscopy (NEWS)
  - Van Den Abeele et al (*RNDE* 12(1), 2000), Van Den Abeele (*JASA* 122(1), 2007)

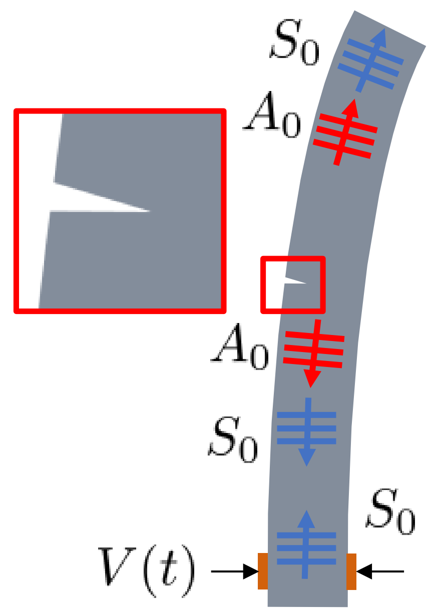
Mode conversion from defects

Mode conversion can be useful as a damage indicator

- Sizing, location, type of defect
- Can be inconclusive!

Ex: Lamb mode NDE of *closed* versus *open* cracks

Closed crack:
No scattering of US signal

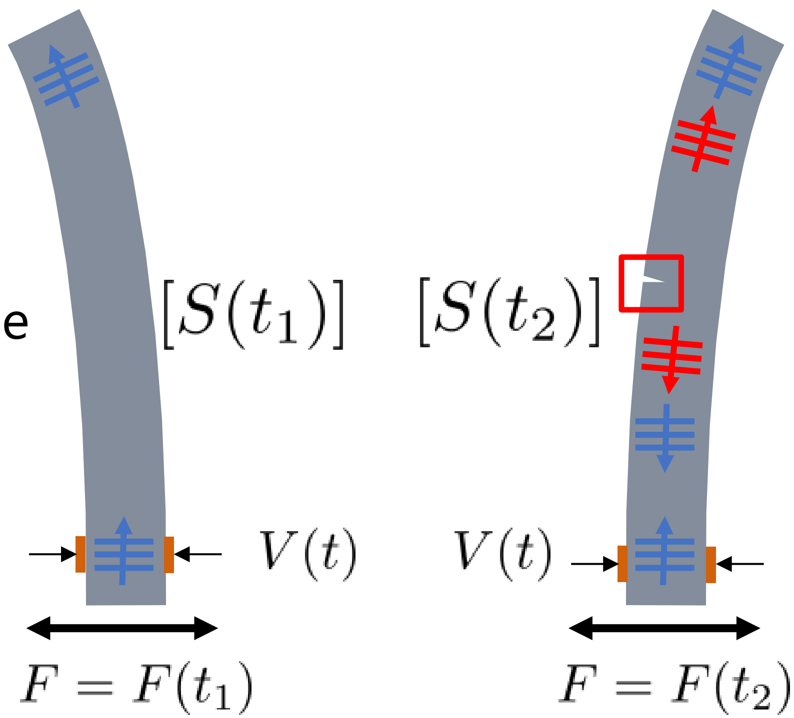


Open crack:
Scattering of US signal

DATM: a pump-probe technique for beams

Dynamic **A**symmetric **T**ransmission **M**easurement

SD "Compression" cycle **closes** crack



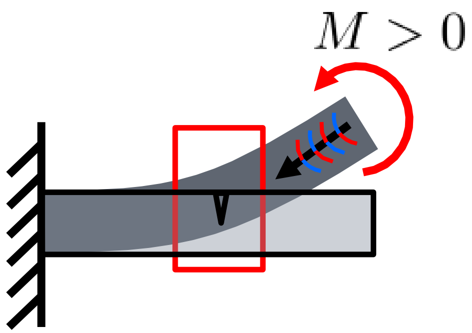
SD "Tension" cycle **opens** crack

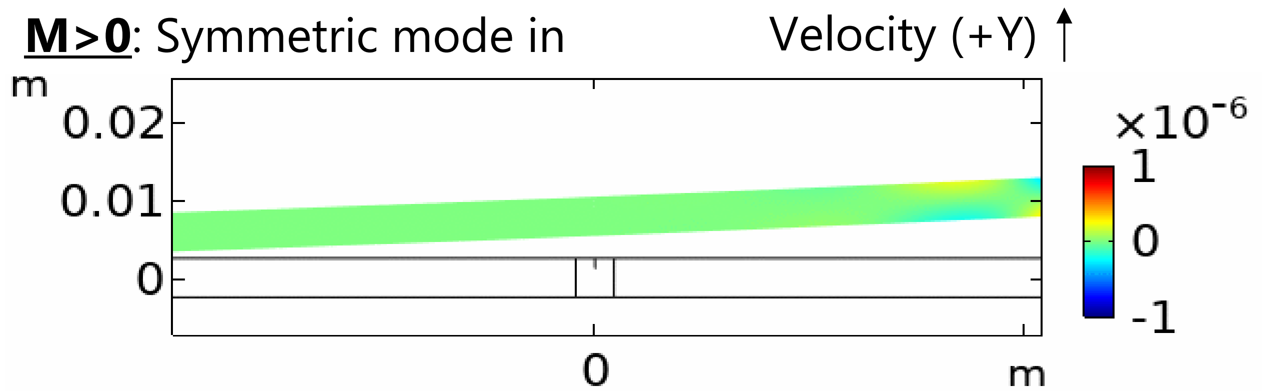
Guided US waves are scattered asymmetrically with respect to the large-scale dynamics of the structure

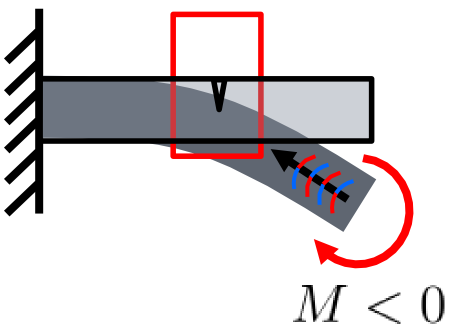
Finite element validation

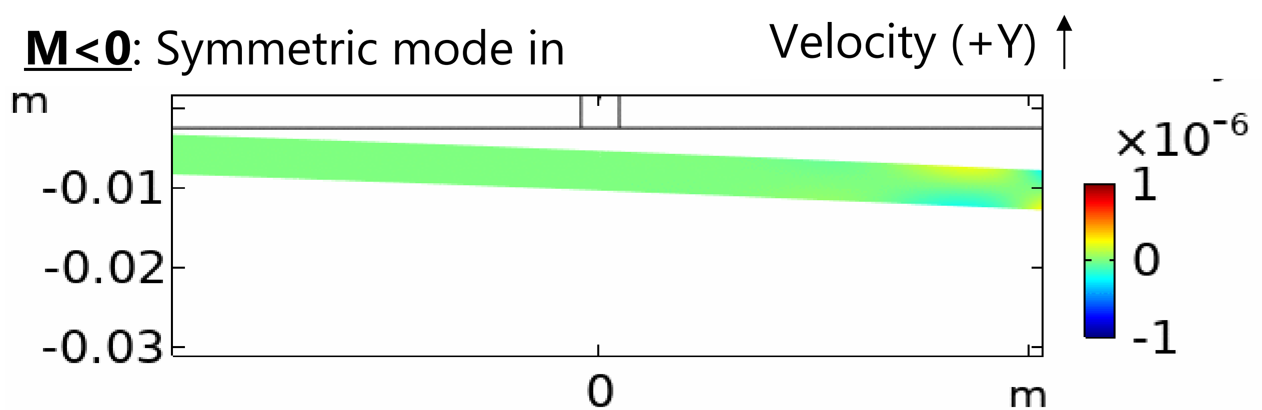
COMSOL Multiphysics used: multistep process

- Static background stress state, transient scattering





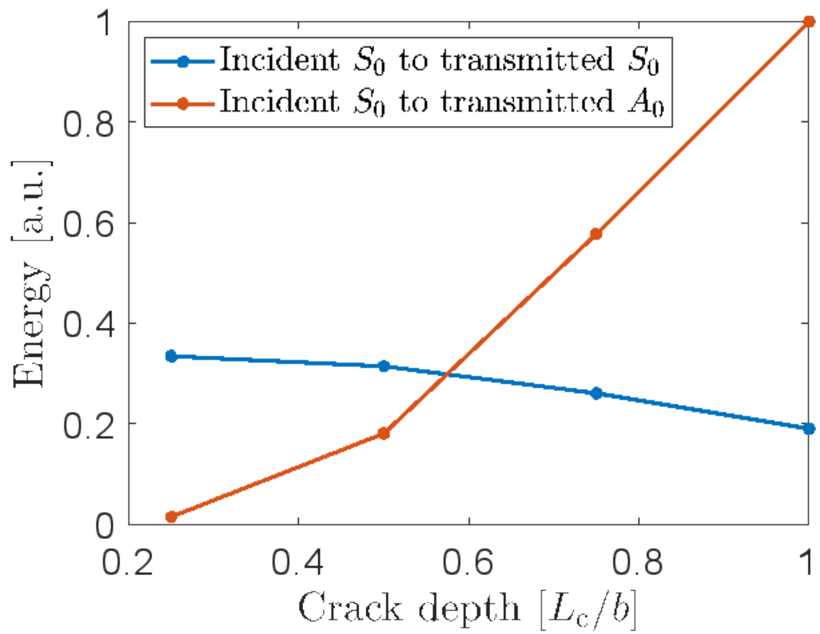




Finite element results: opened crack

Mode conversion varies with depth of crack

- Well-known characterization approach!
- See J.L. Rose's *Ultrasonic Waves in Solid Media* (2004)



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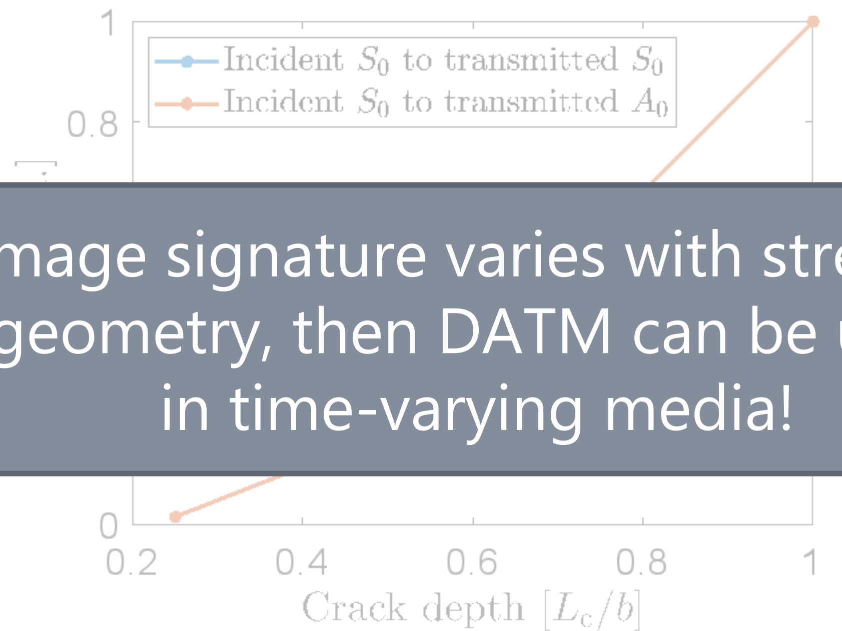

If the damage signature varies with stress state and damage geometry, then DATM can be used for NDE in time-varying media!

Experimental validation

Want to experimentally validate FEA results:

- Observe time-varying mode conversion
- **Quasistatic** stress state with respect to the US signal

We need to:

1. Modulate the structure
2. Measure and link the SD state to a given US pulse
3. Extract the S_n and A_n Lamb waves from a S_n source

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Experimental validation

Want to experimentally validate FEA results:

- Observe time-varying mode conversion
- **Quasistatic** stress state with respect to the US signal
  - Frequency: ~100 Hz for pump, 50 kHz for probe
  - Repetition: 500 Hz probe repetition
  - Amplitude: $|A_{\text{pump}}| >> |A_{\text{probe}}|$

We need to:

1. Modulate the structure
2. Measure and link the SD state to a given US pulse
3. Extract the S_n and A_n Lamb waves from a S_n source

Experimental validation

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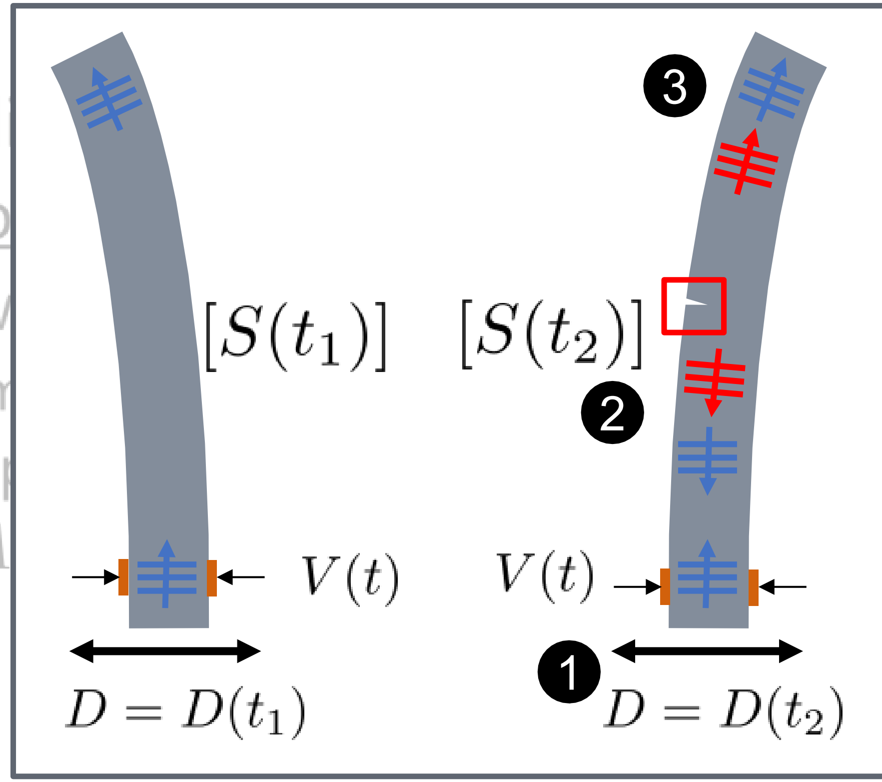
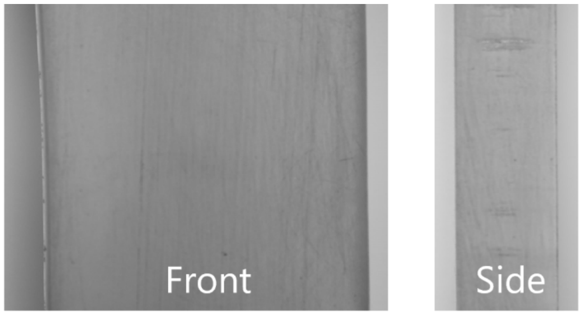


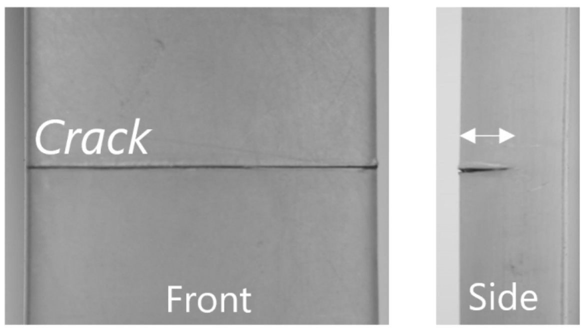
We need to:

1. Modulate the structure
2. Measure and link the SD state to a given US pulse
3. Extract the S_n and A_n Lamb waves from a S_n source

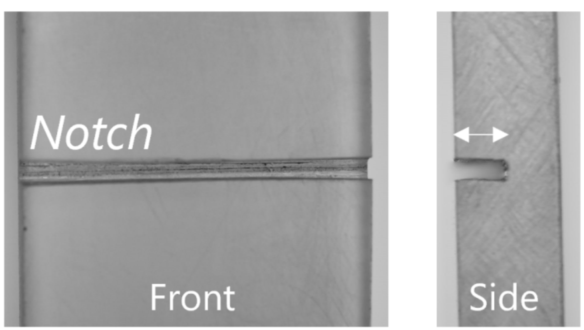
Test articles: Polycarbonate beams



Healthy beam:
- Predominately symmetric energy
- No mode conversion with time
- Near - constant trans. energy

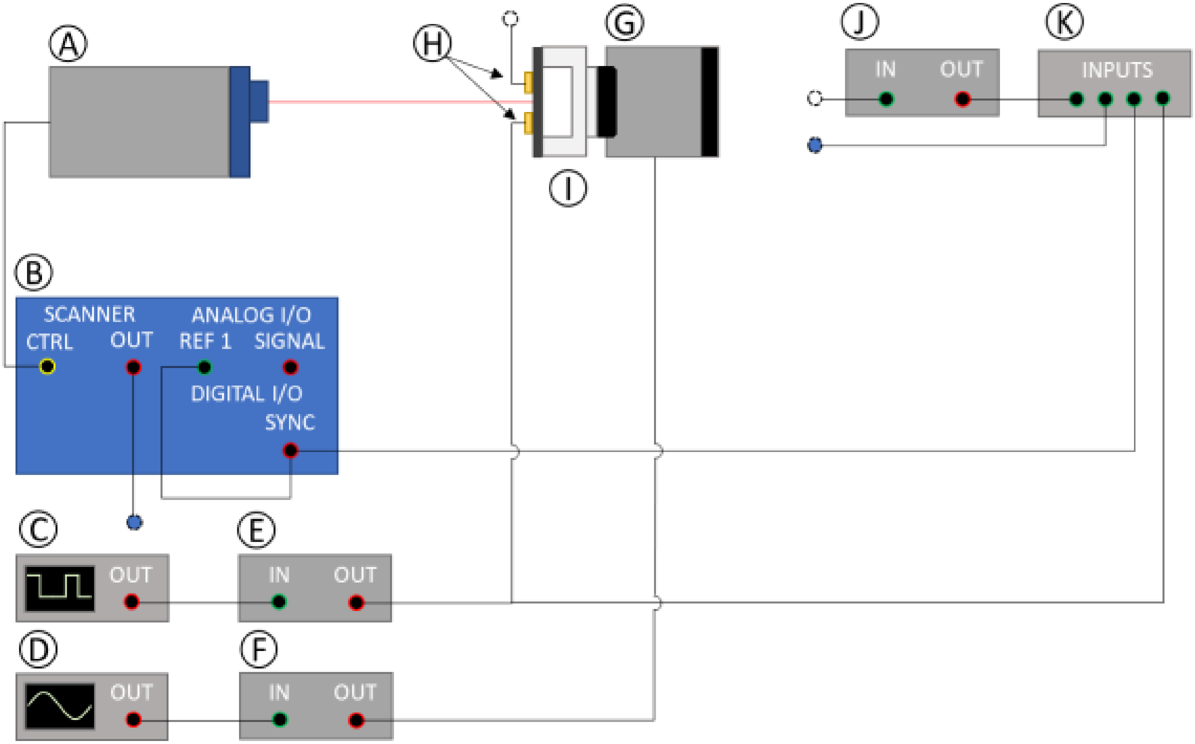


Cracked beam:
- Observed mode conversion
- Mode conversion with time
- Trans. energy varies with time



Notched beam:
- Observed mode conversion
- No mode conversion with time
- Near - constant trans. energy

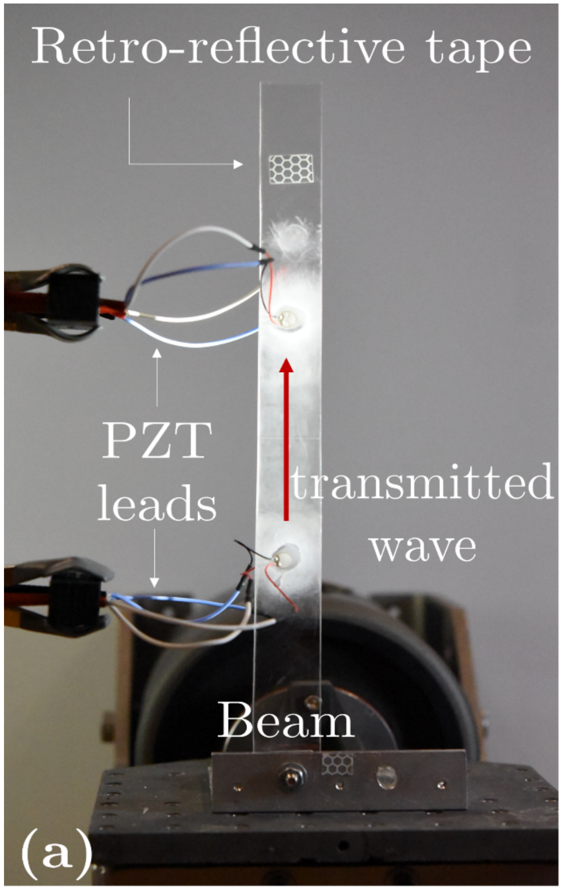
Experimental setup



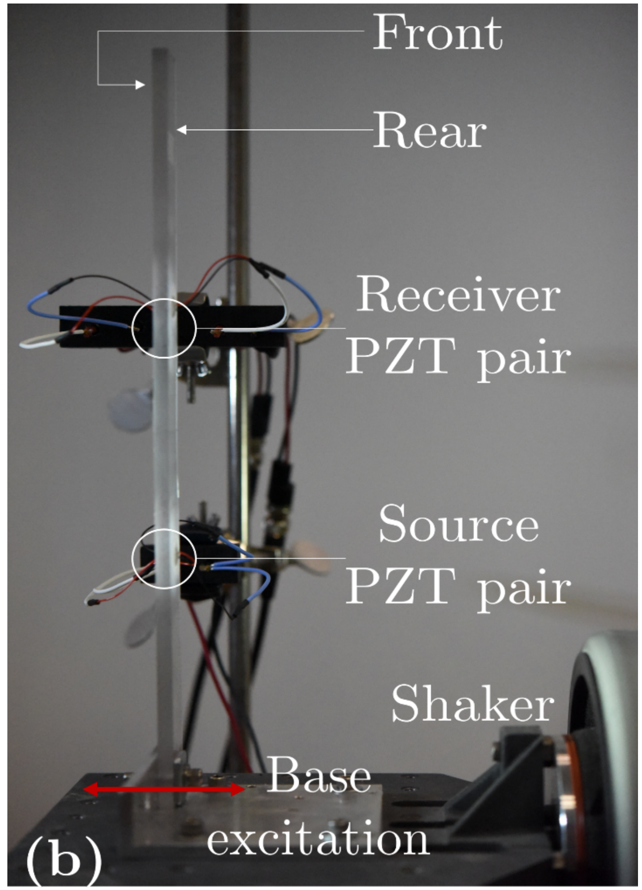
A. LDV scanning head
B. LDV controller
C. Function generator for ultrasonic system
D. Function generator for shaker system
E. Amplifier for ultrasonic system
F. Amplifier for shaker system
G. Electromechanical shaker
H. Ultrasonic PZT transducers
I. Test object
J. Ultrasonic preamplifier and filter
K. Data acquisition system

Next talk (5pPA10) describes in detail how this system works!

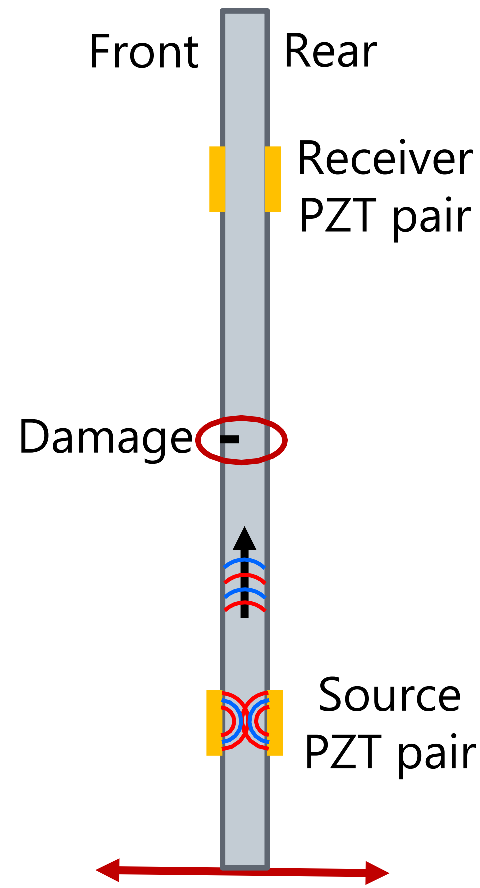
Experimental setup



Front view

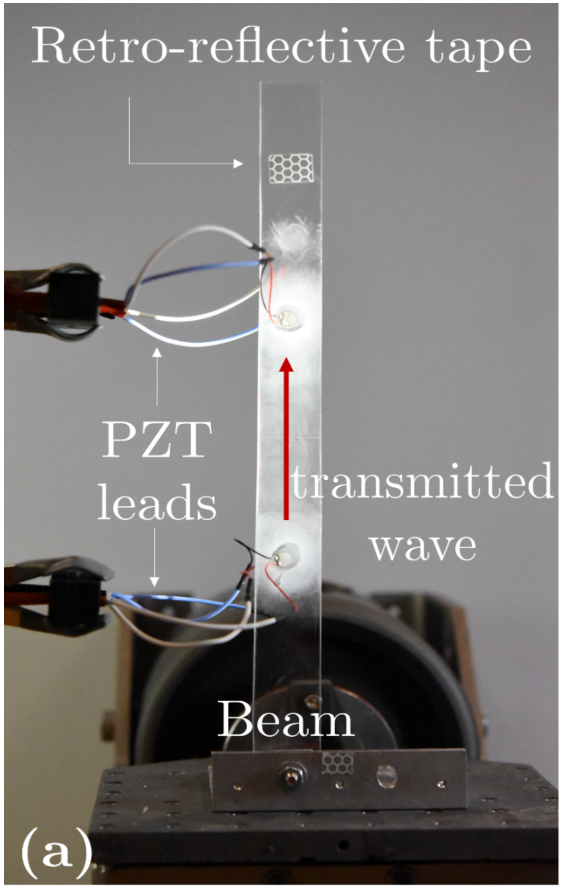


Side view

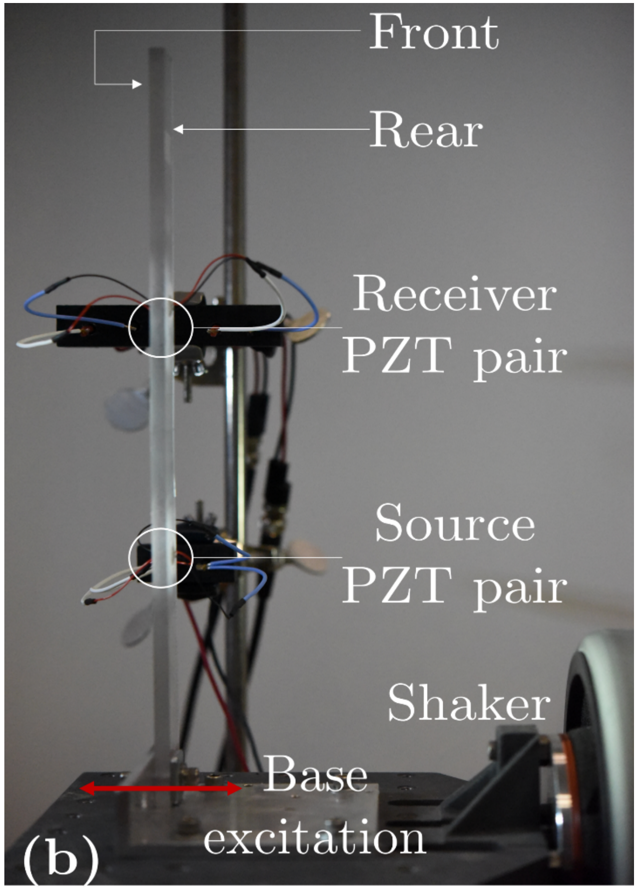


Displacement
from shaker

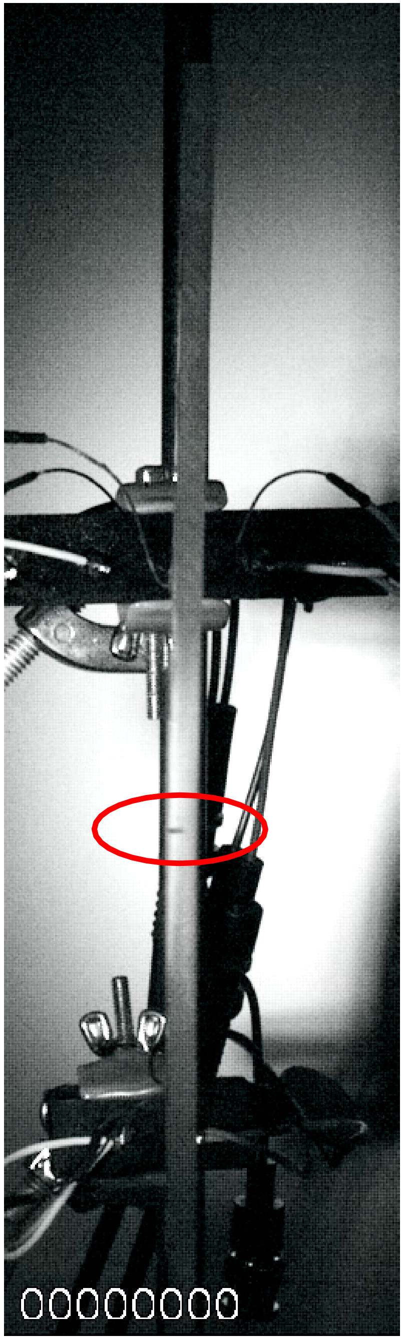
Experimental setup



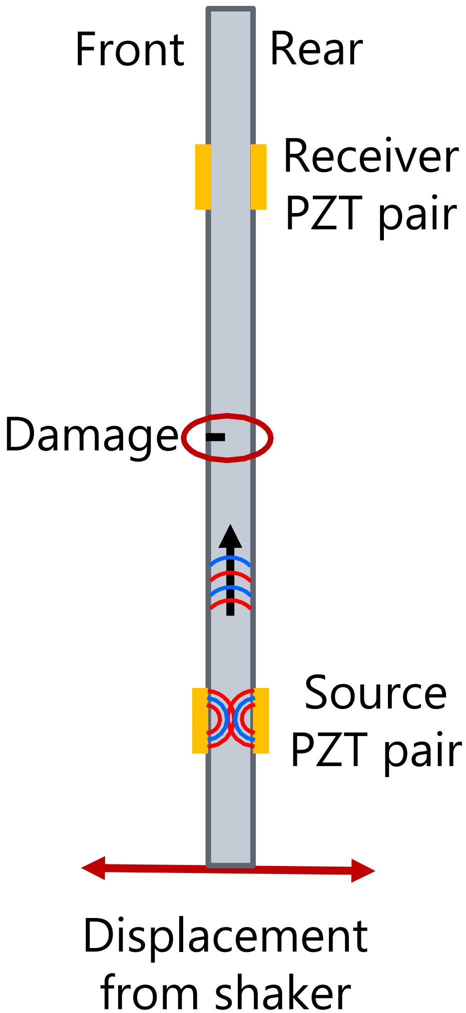
Front view

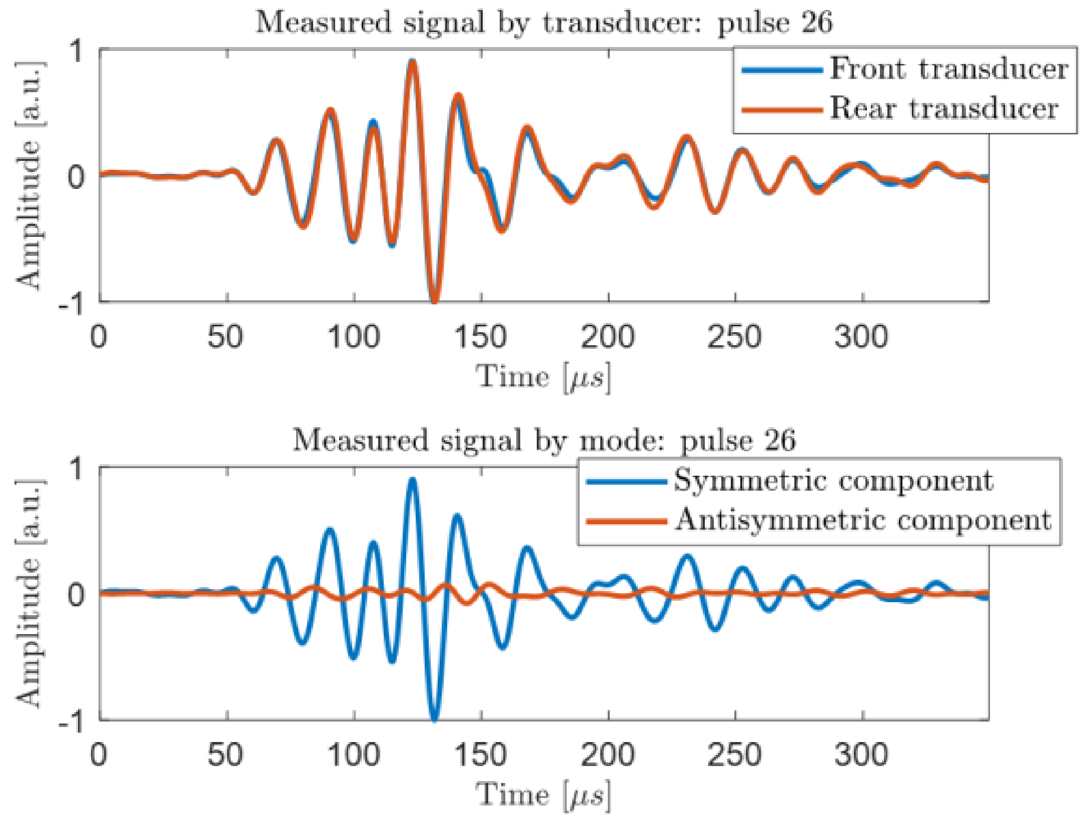


Side view



Processing

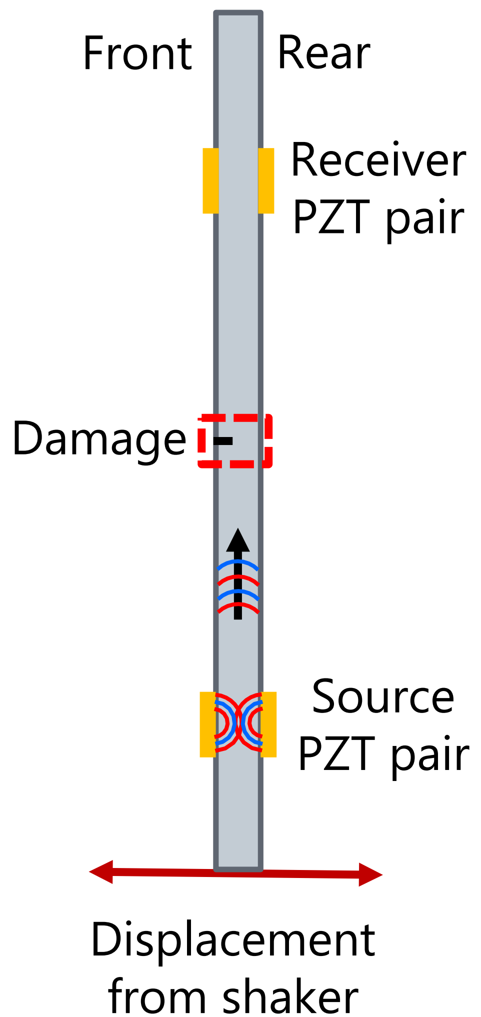




$$V_{\text{sym}} = \frac{1}{2}\left(V_{\text{front}} + V_{\text{rear}}\right)$$

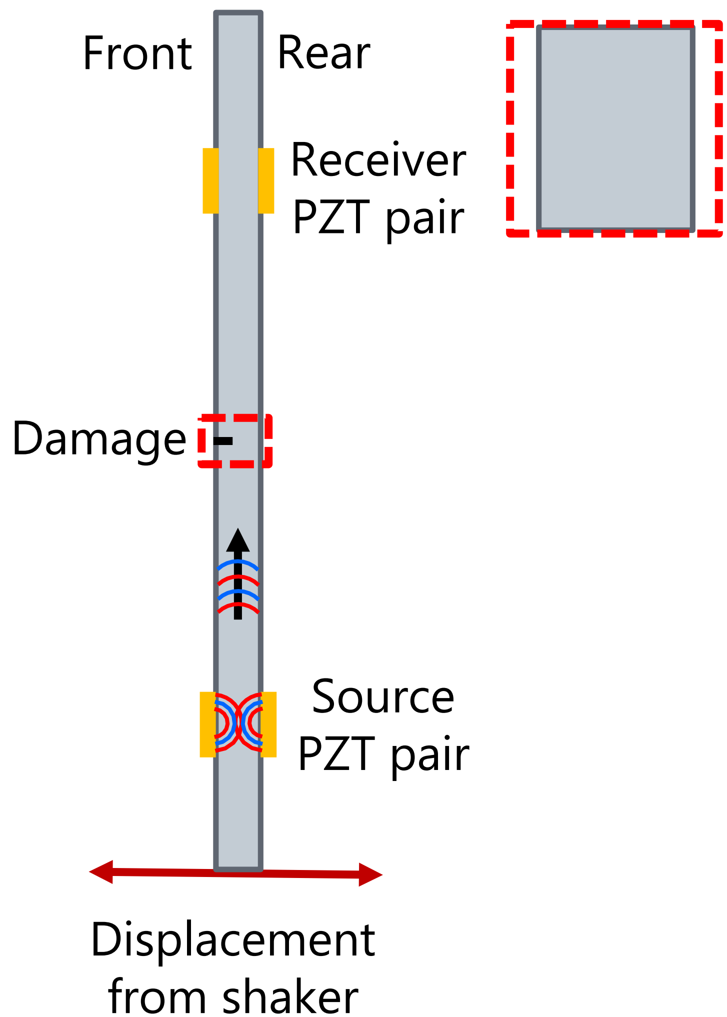
$$V_{\text{anti}} = \frac{1}{2}\left(V_{\text{front}} - V_{\text{rear}}\right)$$

Results

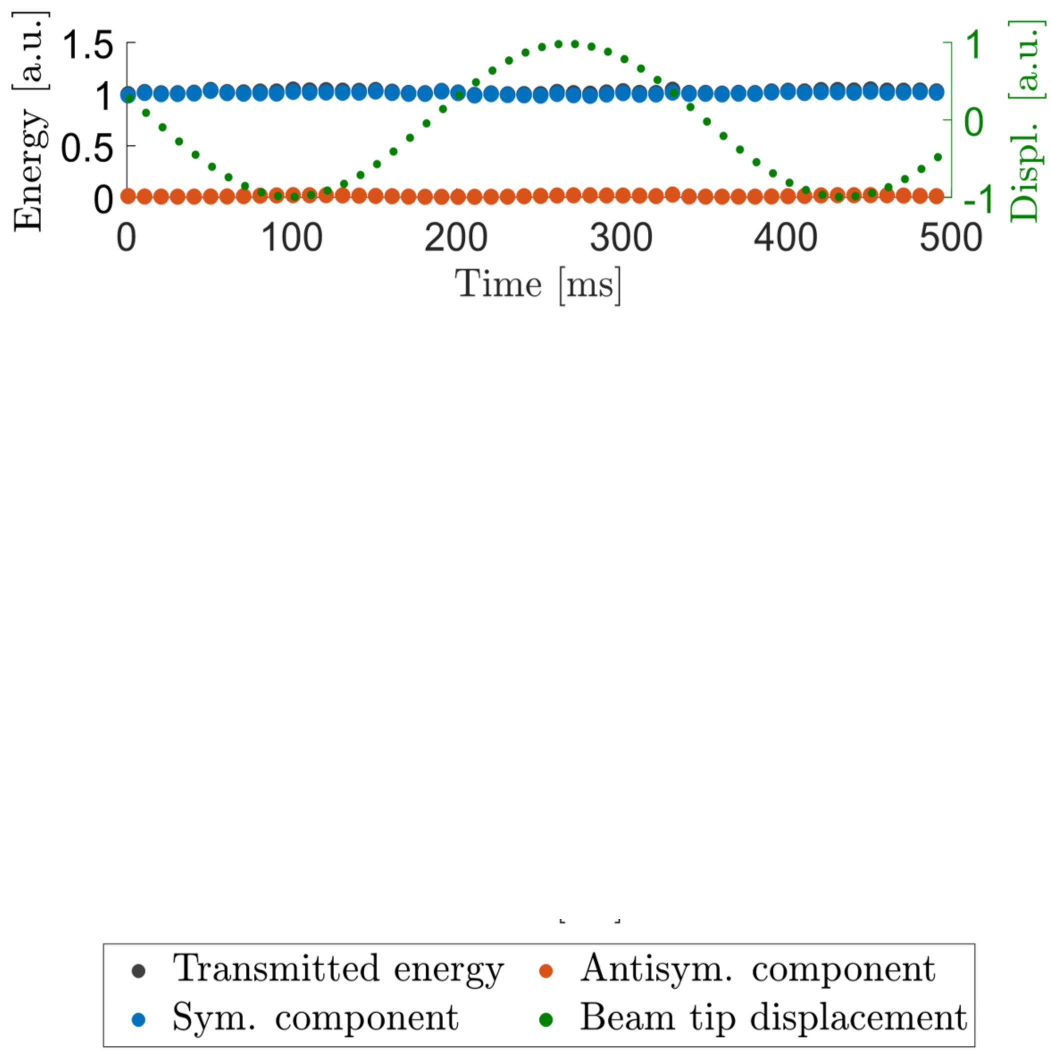


- Transmitted energy
- Antisym. component
- Sym. component
- Beam tip displacement

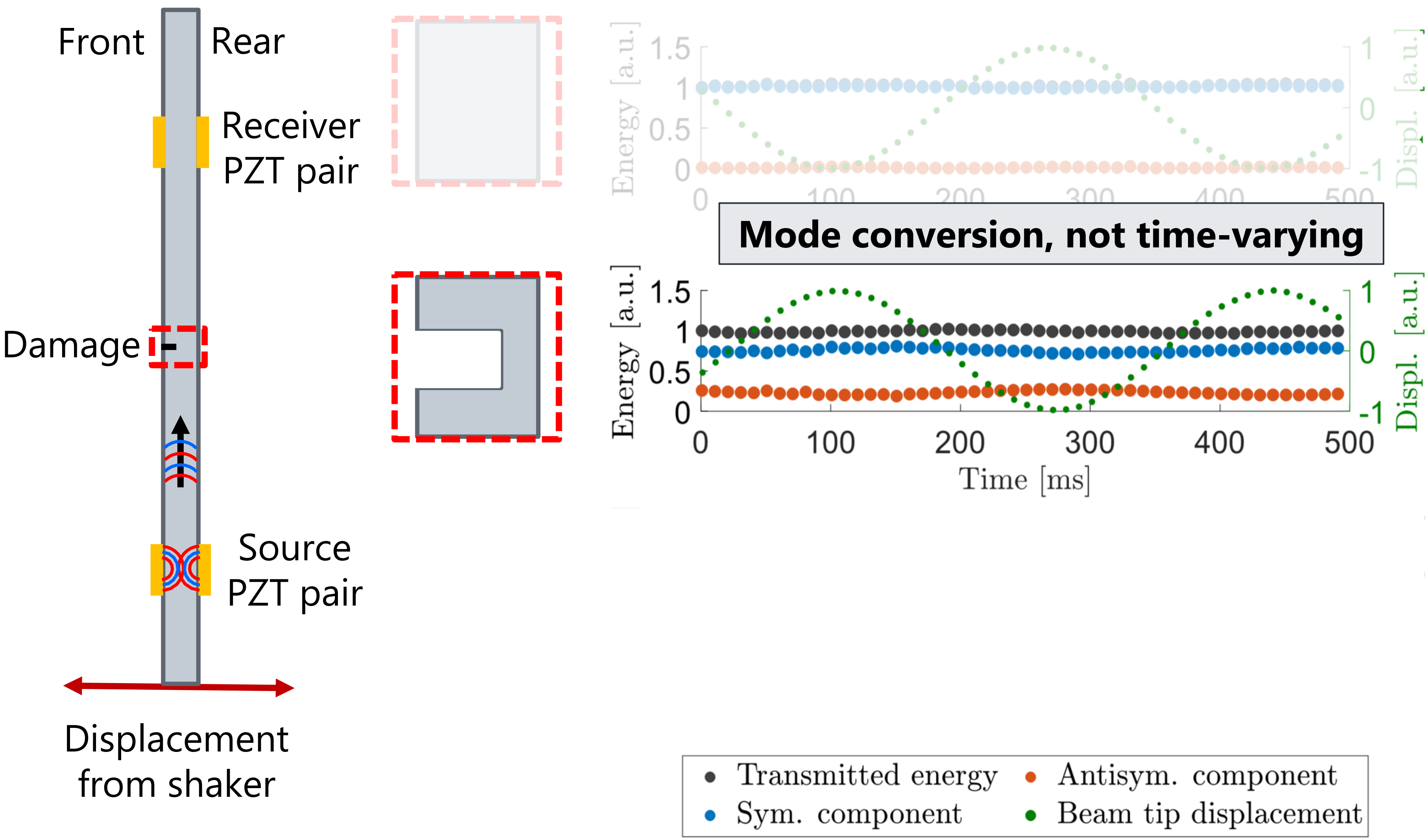
Results



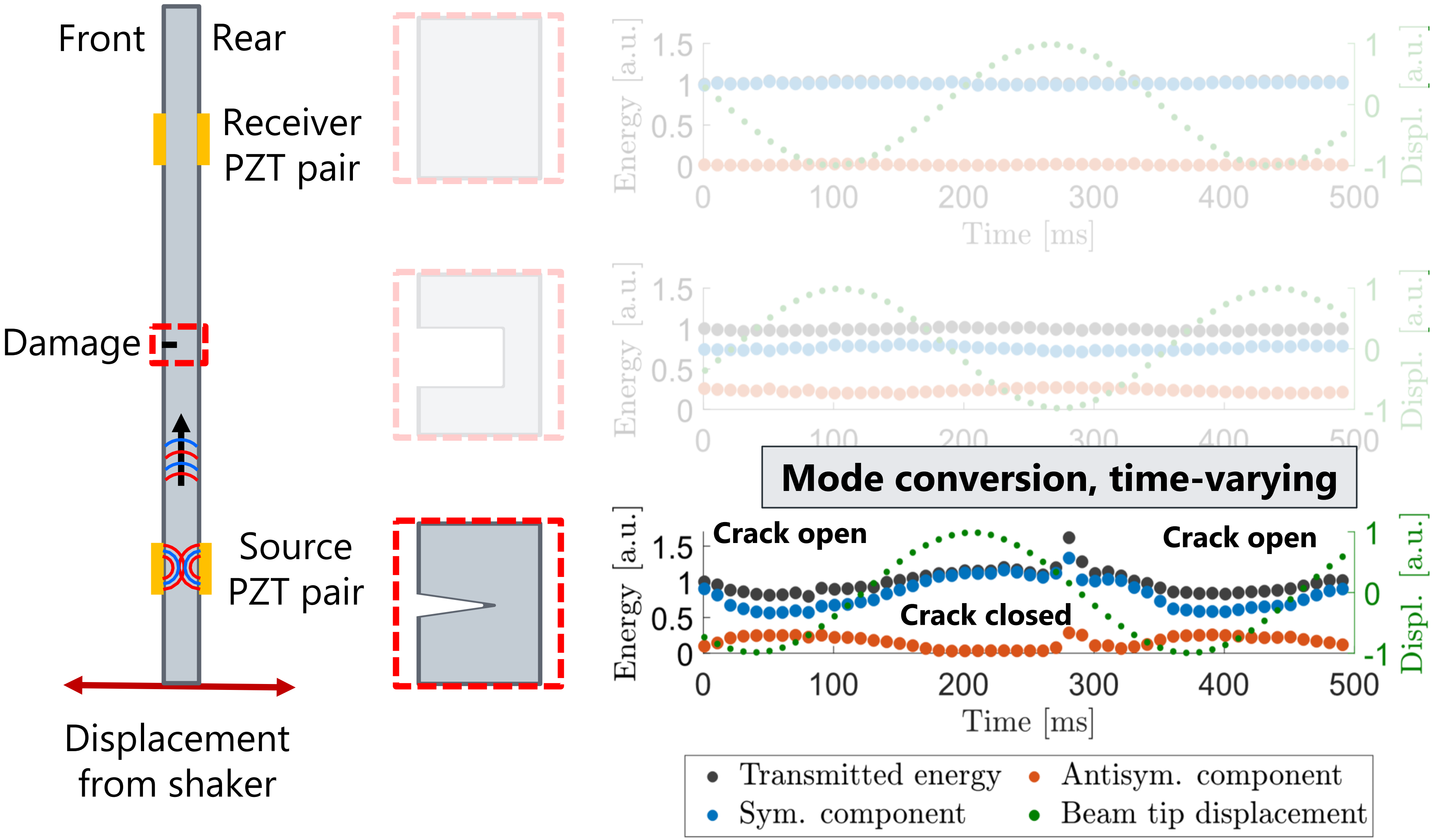
No mode conversion, not time-varying



Results

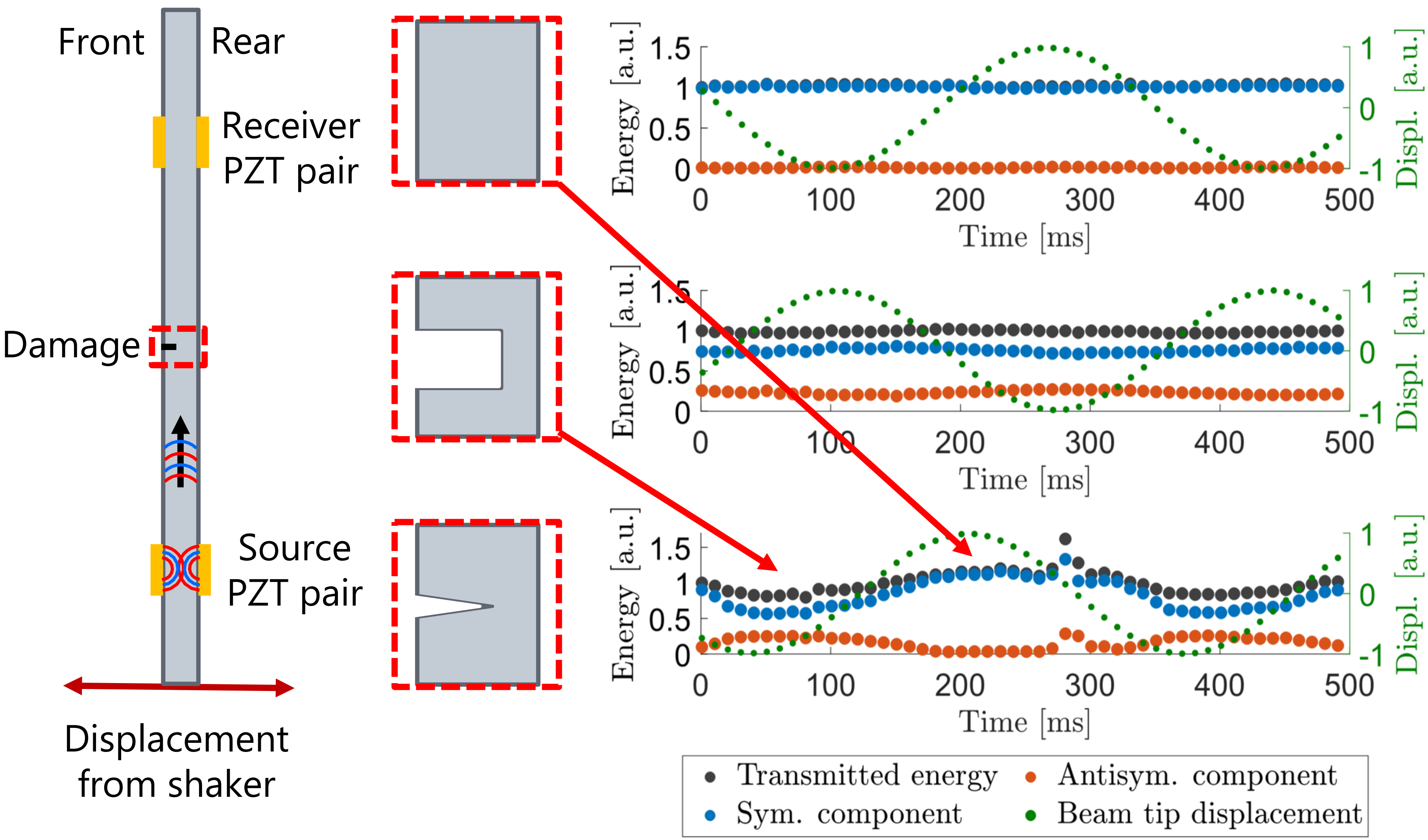

Front
Rear
Receiver
PZT pair
Damage
Source
PZT pair
Displacement
from shaker
Mode conversion, not time-varying
Energy [a.u.]
Displ. [a.u.]
1.5
1
0.5
0
-1
0
100
200
300
400
500
Time [ms]
Transmitted energy
Antisym. component
Sym. component
Beam tip displacement

Results


Front
Rear
Receiver PZT pair
Damage
Source PZT pair
Displacement from shaker
Mode conversion, time-varying
Crack open
Crack closed
Crack open
Energy [a.u.]
Displ. [a.u.]
Time [ms]
Transmitted energy
Antisym. component
Sym. component
Beam tip displacement

Results

Healthy and notch are bounding cases



Applications of DATM

DATM has potential to be used as both a diagnostic tool and design methodology for complex plate structures

Diagnostic tool:

- Short-time scale: detect, locate, characterize
- Long-time scale: monitor growth

Applications of DATM

DATM has potential to be used as both a diagnostic tool and design methodology for complex plate structures

Diagnostic tool:

- Short-time scale: detect, locate, characterize
- Long-time scale: monitor growth

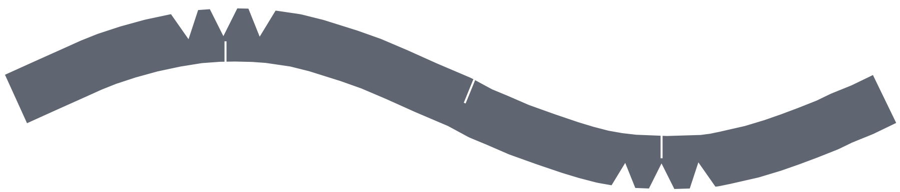
Design tool:

- Patterned geometry: easily-implemented mode converter
  - Semi-analytical methods for forward/inverse solutions
- Selective transmission: US transmission linked to SD mode

Applications of DATM

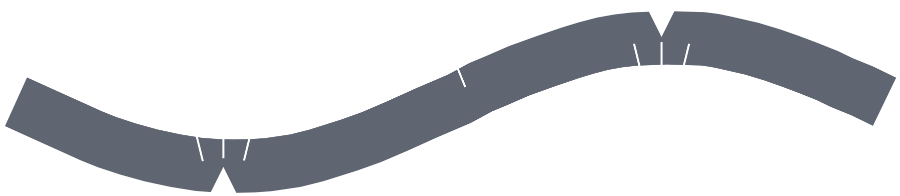
Proposed metamaterial beam: $$[S] = [S(\omega, \phi)]$$

$S_0 \text{ in}, \omega_1$



$$[S(\omega_1, \phi)] \begin{Bmatrix} S_0 \\ A_0 \end{Bmatrix}$$

$S_0 \text{ in}, \omega_1$



$$[S(\omega_1, \phi + \pi)] \begin{Bmatrix} S_0 \\ A_0 \end{Bmatrix}$$

$S_0 \text{ in}, \omega_0$

$$[S(\omega_0, \phi)] \begin{Bmatrix} S_0 \\ A_0 \end{Bmatrix}$$

$S_0 \text{ in}, \omega_0$

$$[S(\omega_0, \phi + \pi)] \begin{Bmatrix} S_0 \\ A_0 \end{Bmatrix}$$

Summary

- A pump-probe method for elastic beams was developed
  - DATM: Dynamic asymmetric transmission measurement
  - **Time-varying mode conversion** as an indicator parameter
- DATM has been validated via FEA, experiments
  - Surface-breaking cracks versus notch
- Further work is in progress:
  - NDE and structural health monitoring
  - Metamaterial beam design

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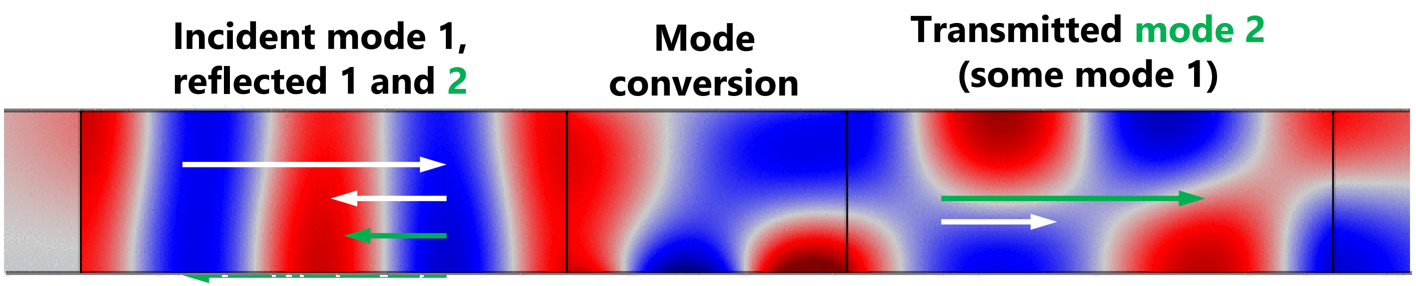
Mode conversion from defects

In addition to nonlinear parameters, **mode conversion** can be used as a linear indicator of damage for NDE

- Unbounded medium: P- and S-waves
- Bounded medium: **Lamb waves** and others

Usually use a baseline:

- Variations in the amount of mode conversion can indicate a change in the system



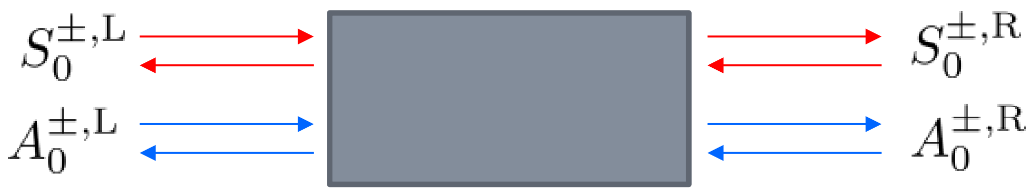
[M. R. Haberman (2022), "The Principle of Reciprocity"]

Time-varying mode conversion

A pump-probe technique based on time-varying mode conversion may be advantageous

- Variation in stress state → variation in scattering
- Modulate scattering by temporal modulation of stress state

$$\vec{U}_{\mathrm{out}} = [S(t)]\vec{U}_{\mathrm{in}}$$

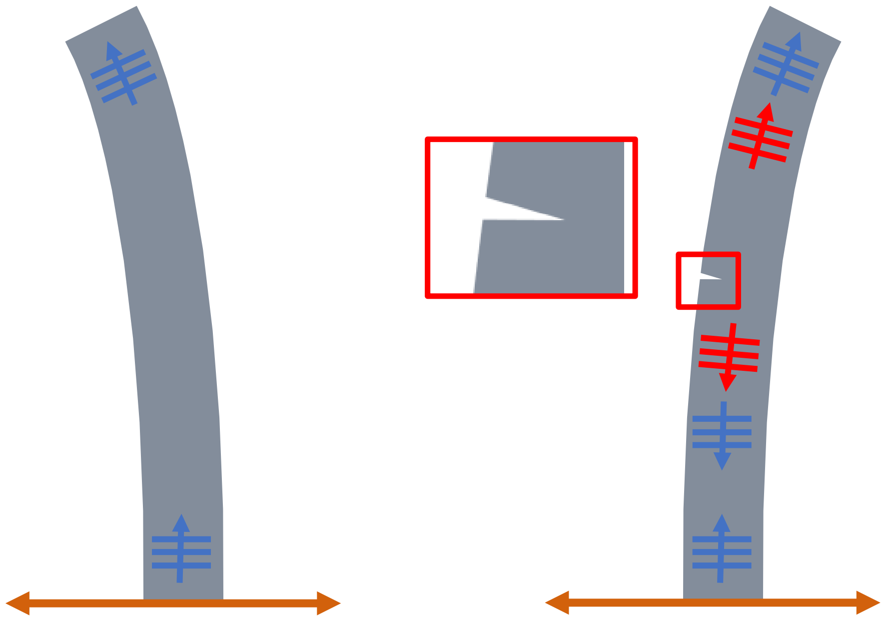


Such a technique may provide advantages over existing NDE and pump -probe techniques

- Reduction in ambiguity of damage type and location
- Experimental flexibility
- Linear versus nonlinear signature

DATM: a pump-probe technique for beams

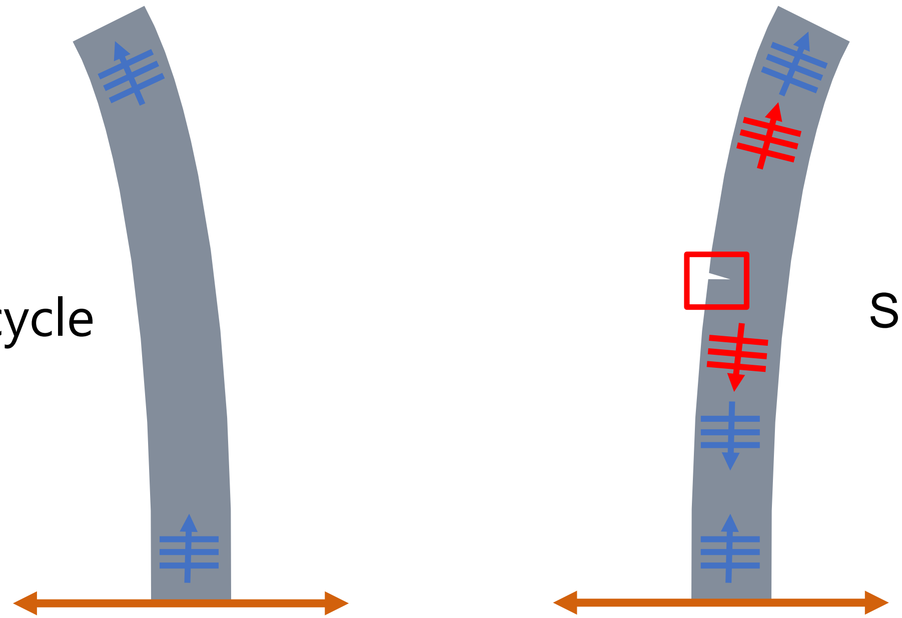
Dynamic **A**symmetric **T**ransmission **M**easurement



DATM: a pump-probe technique for beams

Dynamic **A**symmetric **T**ransmission **M**easurement

SD "Compression" cycle **closes** crack



SD "Tension" cycle **opens** crack

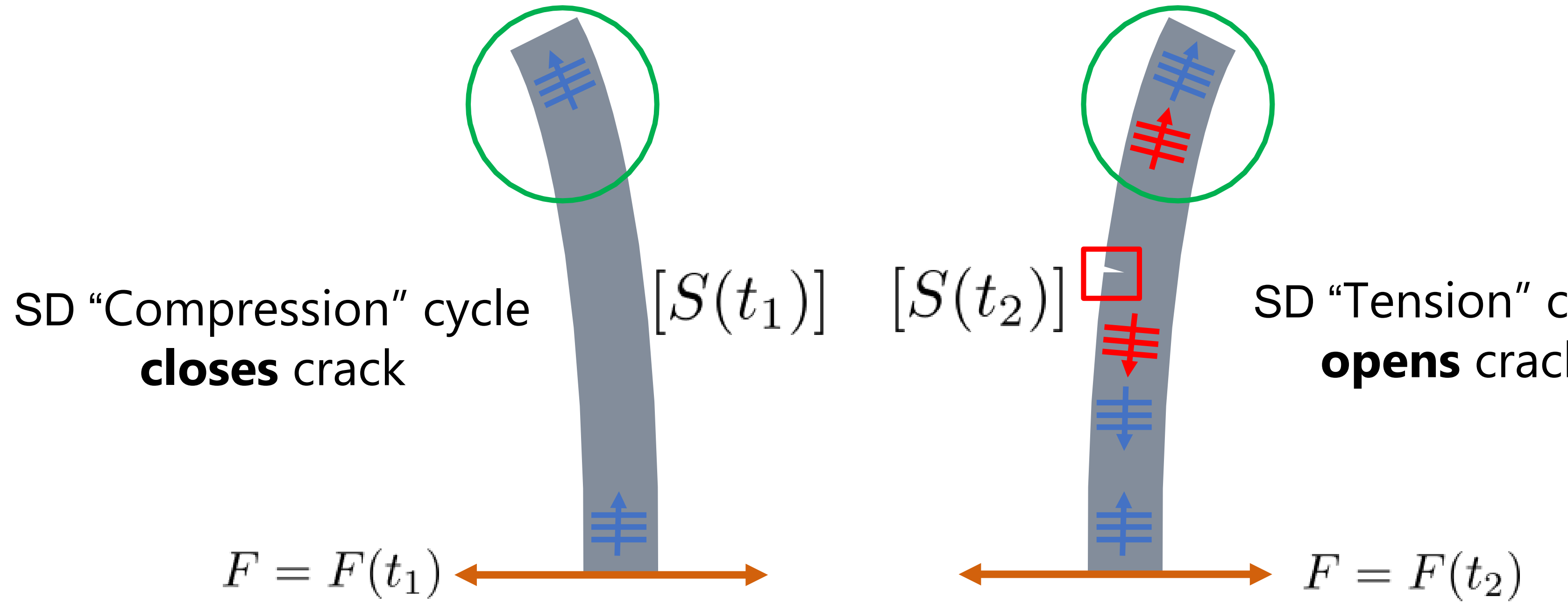
$F = F(t_1)$

$F = F(t_2)$

Large-scale structural excitation causes temporal modulation of the local stiffness at points associated with damage

DATM: a pump-probe technique for beams

Dynamic **A**symmetric **T**ransmission **M**easurement

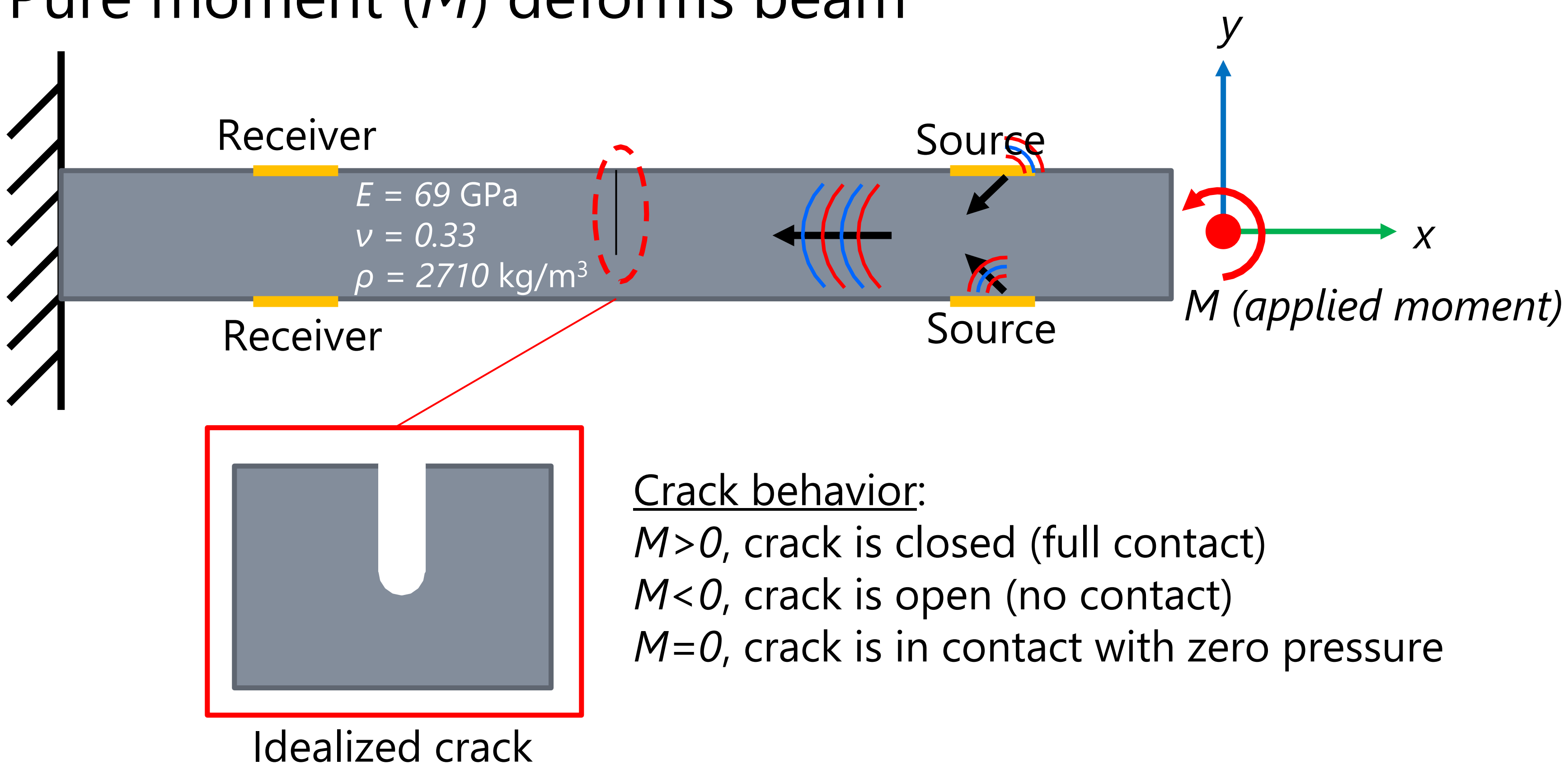


Transmitted scattered US guided waves are measured and linked to a "instantaneous" global dynamic state

Finite element validation

<u>2D plane-strain beam</u>: only S_0, A_0 modes

- Fixed on left side, free on all others
- Pure moment (*M*) deforms beam

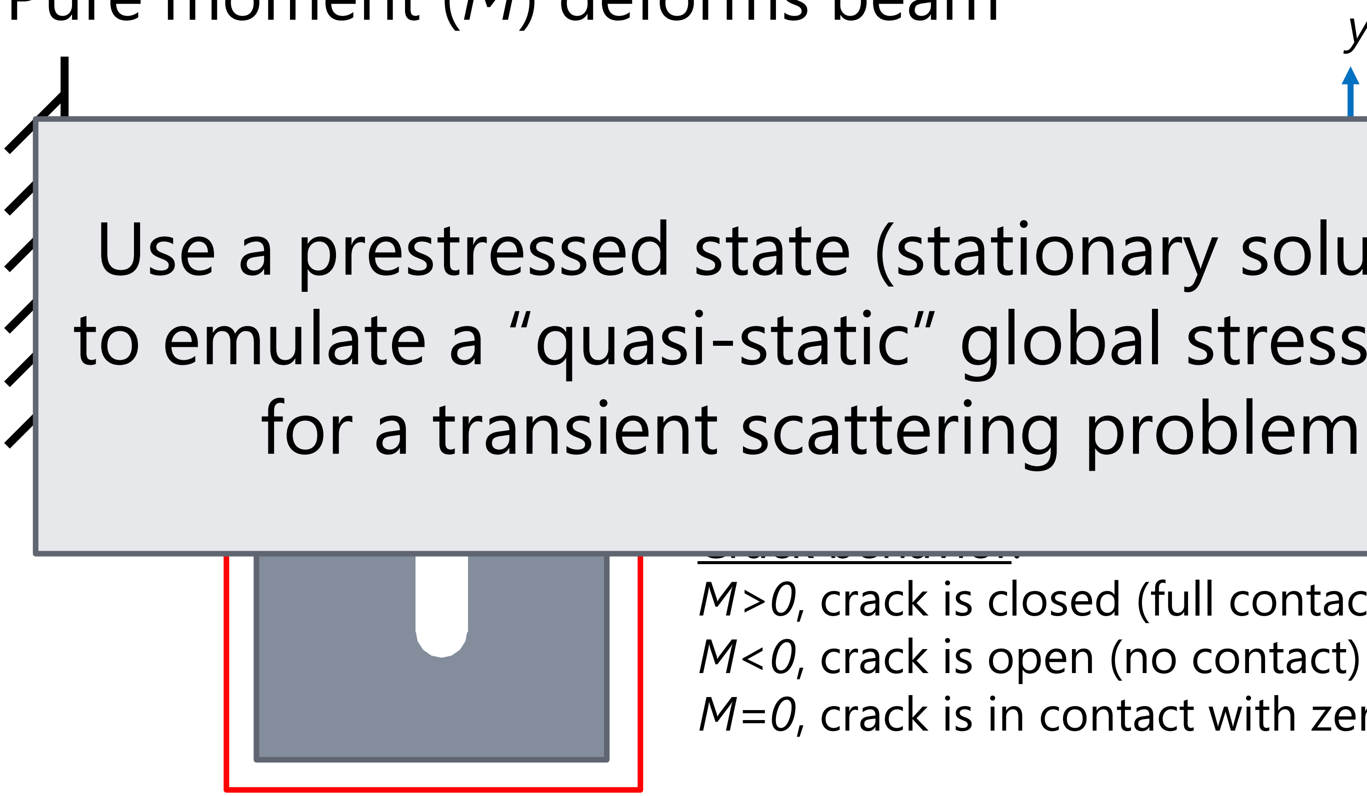


<u>Crack behavior</u>:
M>*0*, crack is closed (full contact)
M<*0*, crack is open (no contact)
M=*0*, crack is in contact with zero pressure

Finite element validation

2D plane-strain beam:

- Fixed on left side, free on all others
- Pure moment (*M*) deforms beam



Use a prestressed state (stationary solution) to emulate a "quasi-static" global stress state for a transient scattering problem

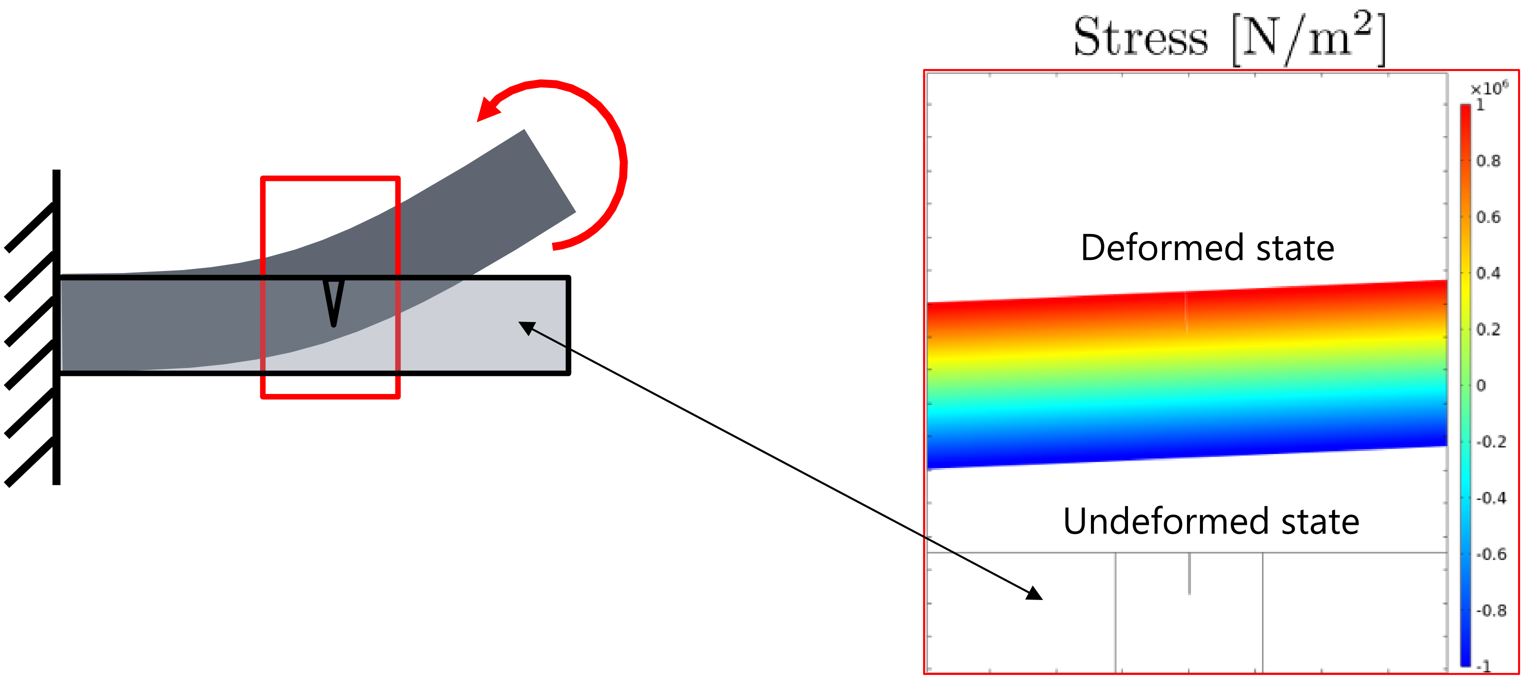
Idealized crack

M>0, crack is closed (full contact)
M<0, crack is open (no contact)
M=0, crack is in contact with zero pressure

Finite element validation

COMSOL Multiphysics used: multistep process

- Nonlinear stationary solver: global stress states

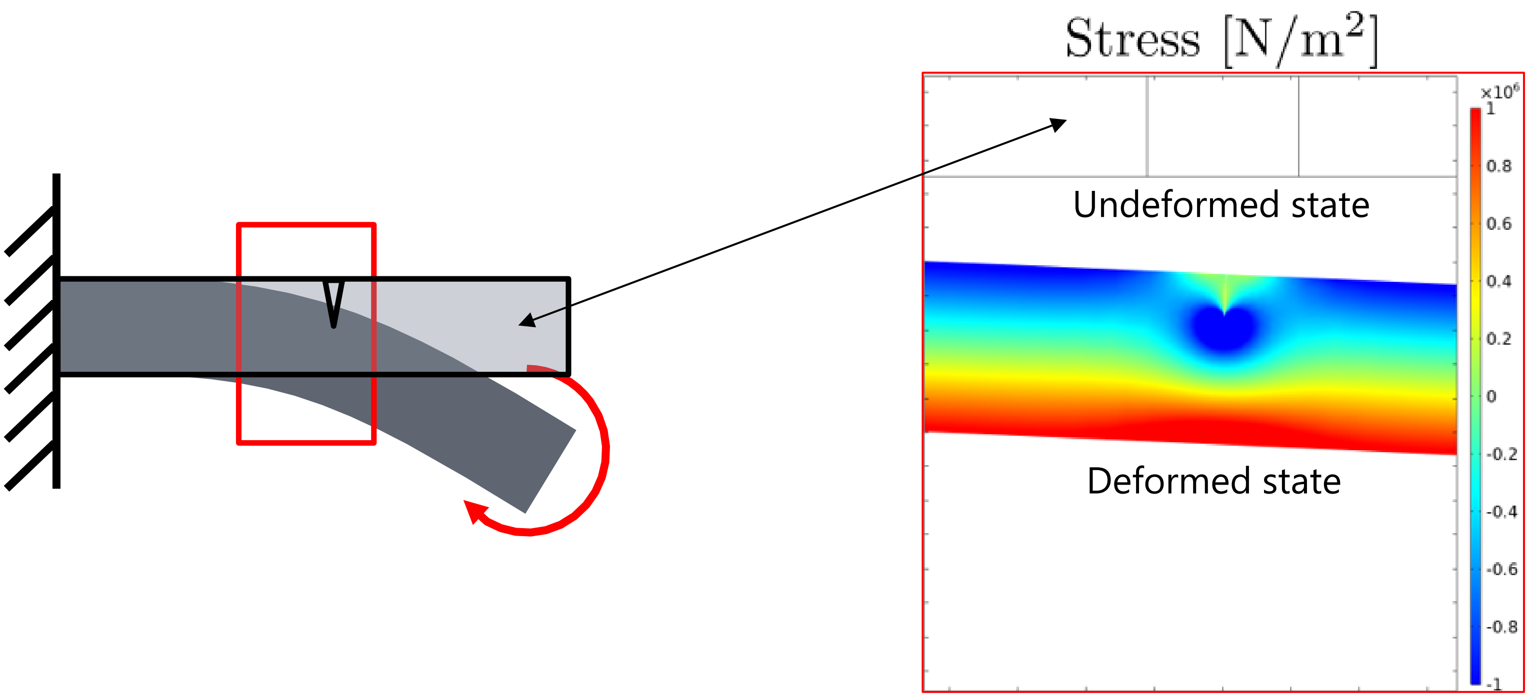


M > 0, crack closed: continuous stress will not cause scattering of incident guided US wave

Finite element validation

COMSOL Multiphysics used: multistep process

- Nonlinear stationary solver: global stress states

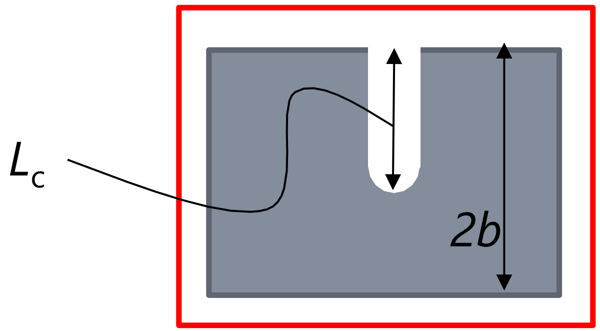


M < 0, crack open: traction-free crack faces will cause scattering of the incident guided US wave

Finite element validation

COMSOL Multiphysics used: multistep process

- Parameter sweep: crack depth



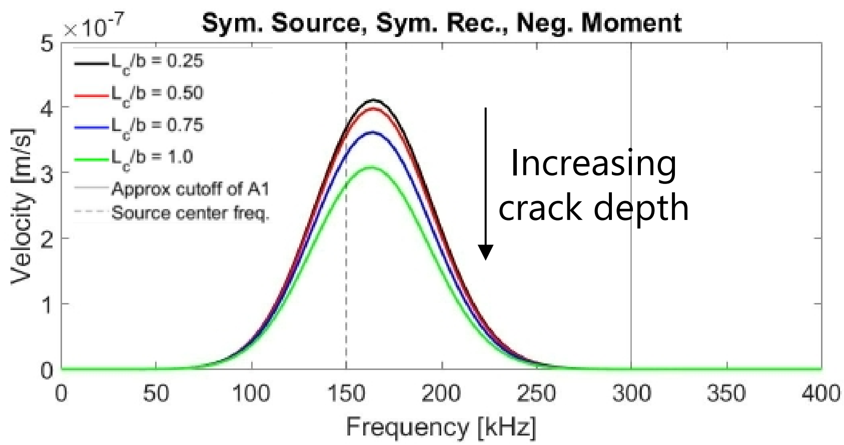
Idealized crack

Crack behavior:
M>0, crack is closed (full contact)
M<0, crack is open (no contact)
M=0, crack is in contact with 0 pressure

Vary L_c as a function of the half-thickness b

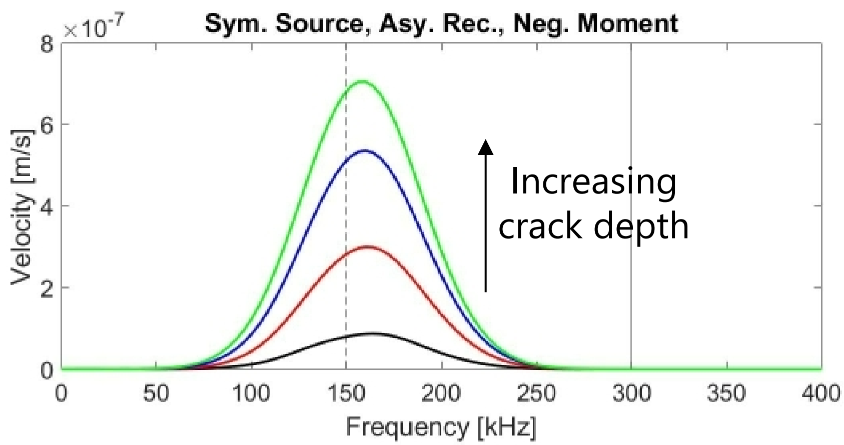
- ¼, ½, ¾, 1 ($\times b$)
- i.e. $b/2$ is a quarter the total beam thickness

Finite element results: opened crack



Incident S_0 to transmitted S_0

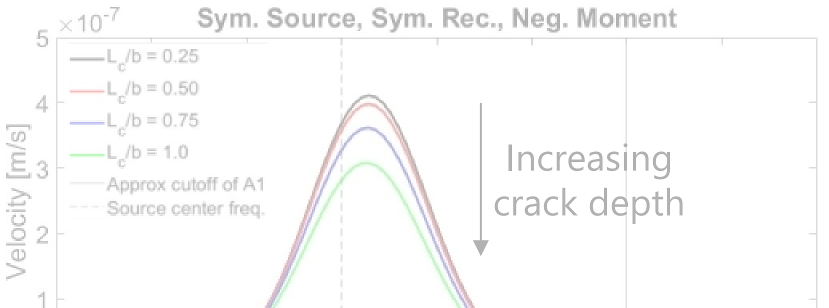
Energy decreases with increasing crack depth



Incident S_0 to transmitted A_0

Energy increases with increasing crack depth

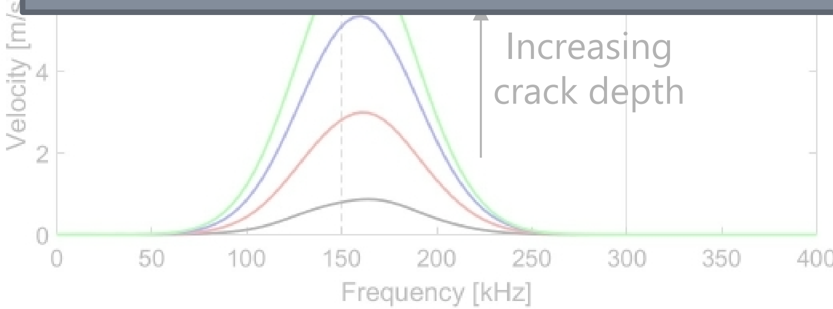
Finite element results: opened crack



Incident S_0 to transmitted S_0

Energy decreases with increasing crack depth

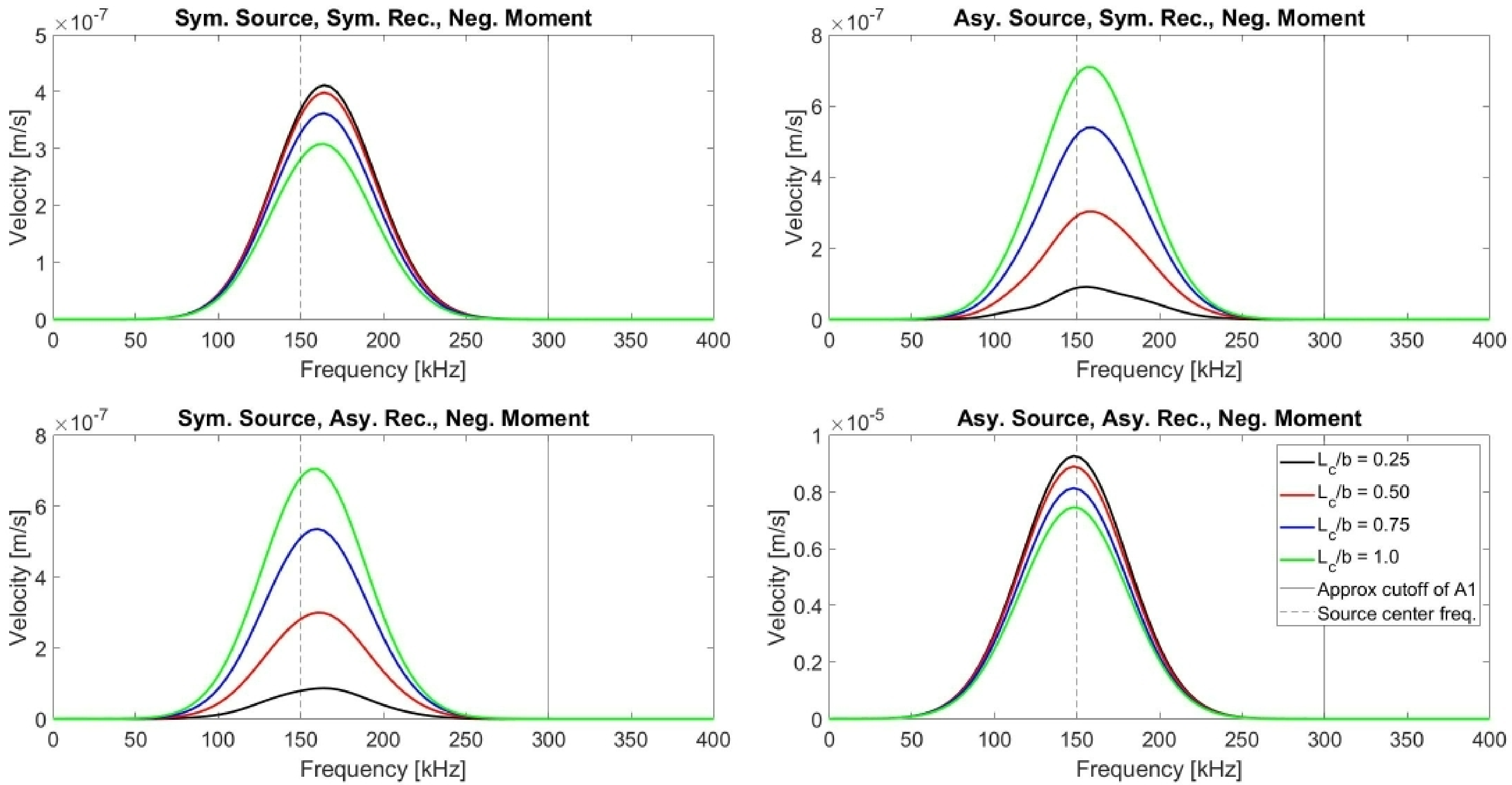
If the damage signature varies with stress state, then DATM can be used for NDE in time-varying media!



Energy increases with increasing crack depth

TEXAS
The University of Texas at Austin

Finite element results: -*M*, open crack



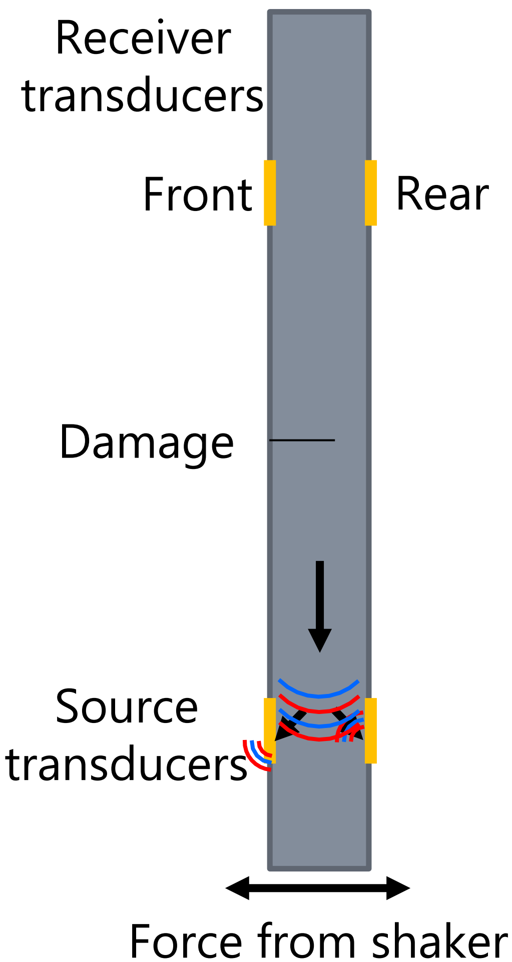
Columns show “scattering pairs” that indicate mode conversion

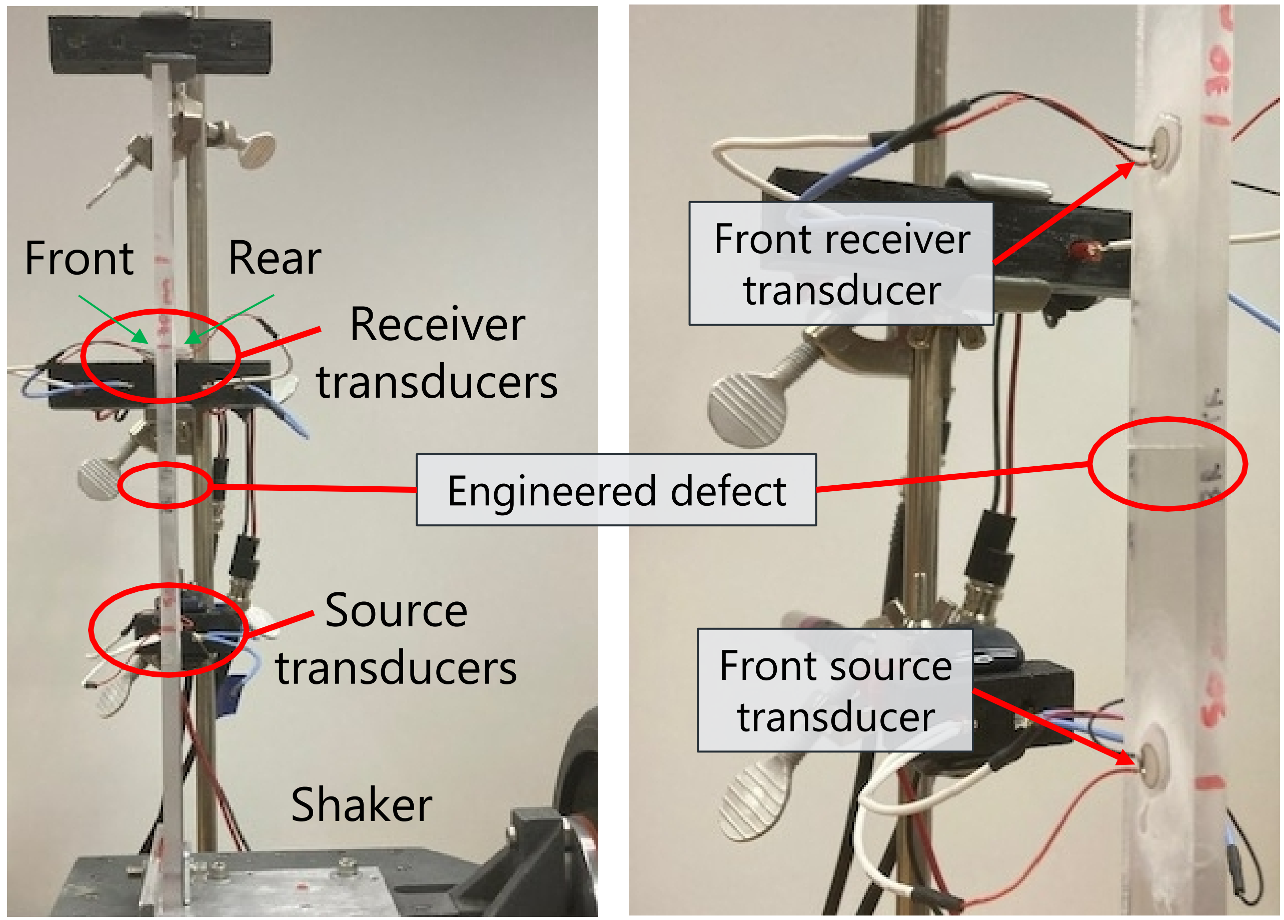
Finite element results

- Global stress state determines scattering of guided US waves in a structure
  - Detection: time-varying mode conversion
  - Location: time of flight of scattered signal
- Mode conversion depends on the depth of the crack
  - Characterization: change in mode conversion

If the damage signature varies with stress state, then DATM can be used to detect, locate, and characterize!

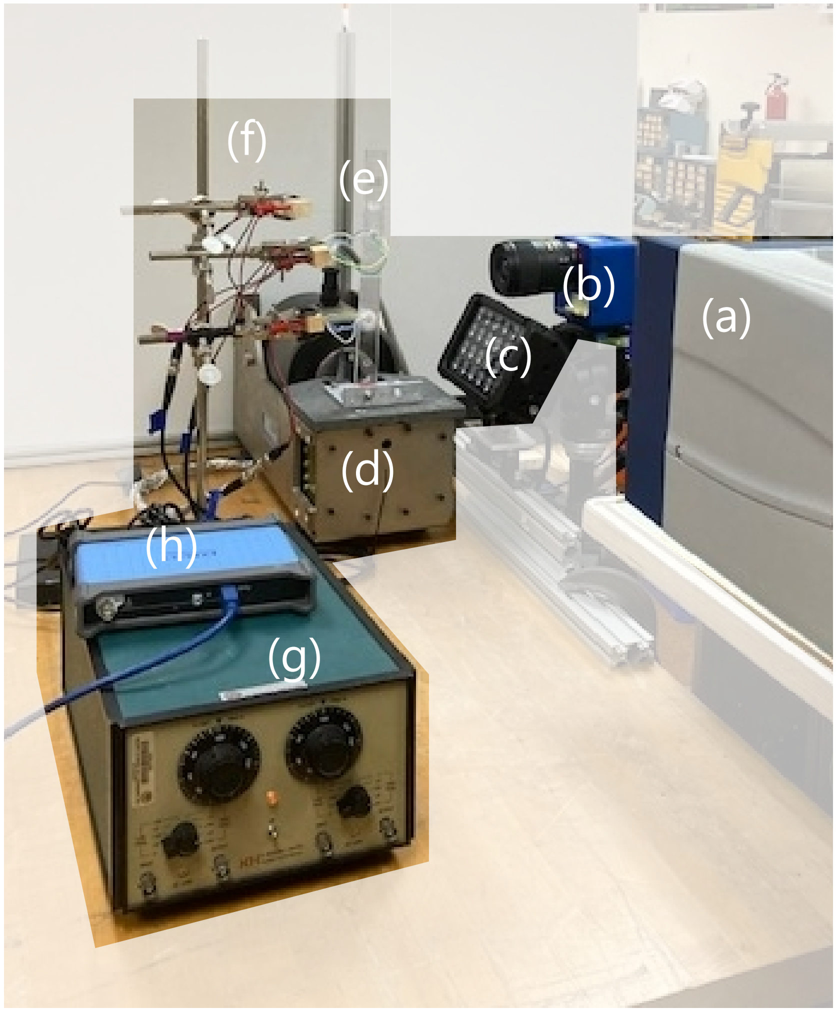
Experimental setup





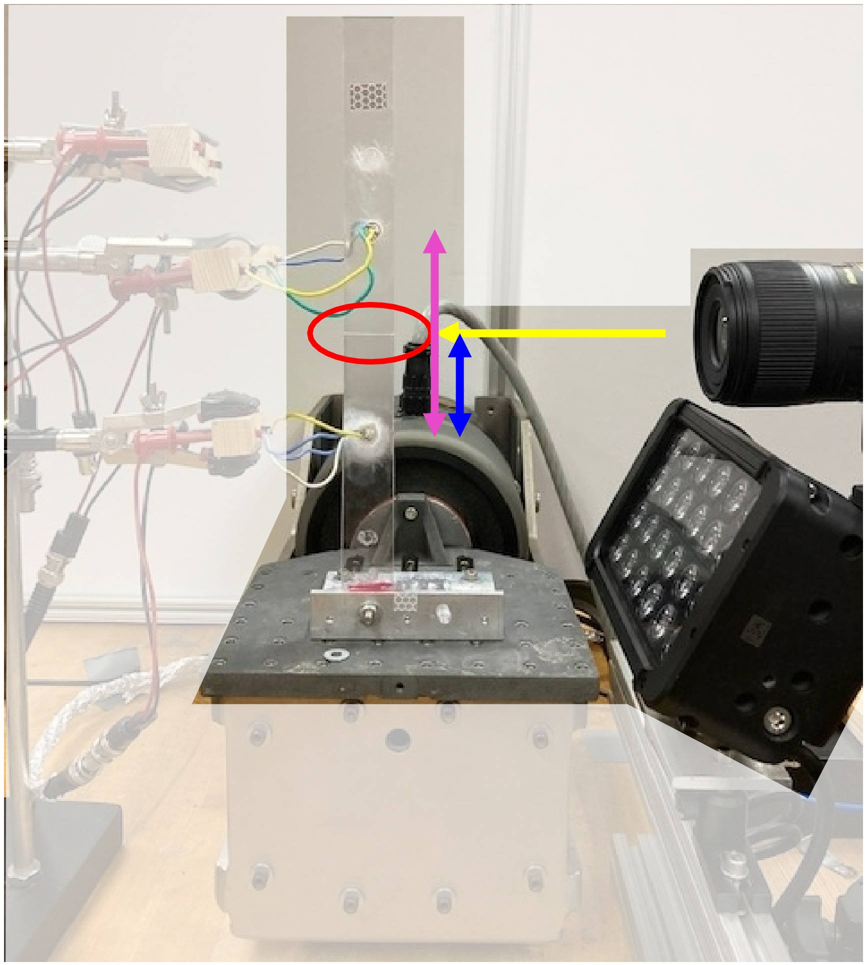
Samples constructed from Polycarbonate

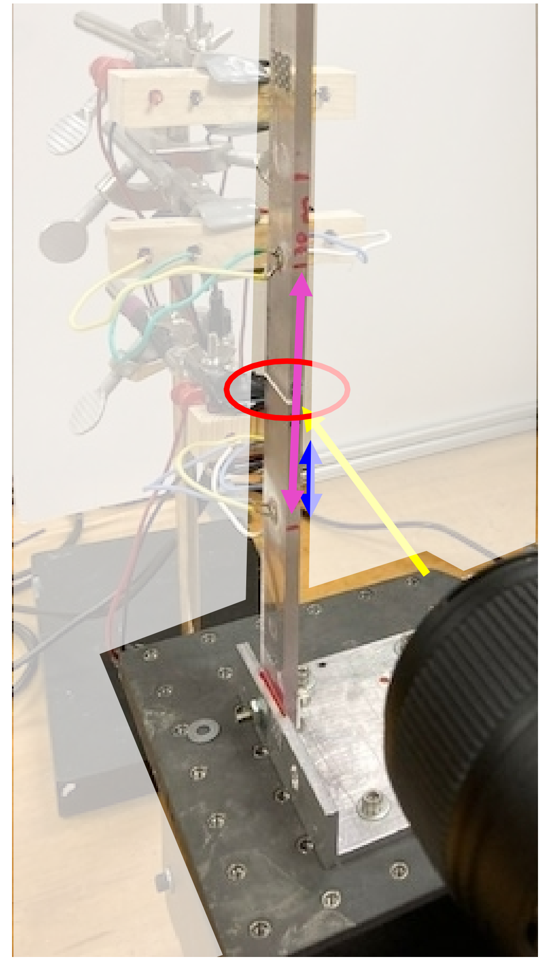
Experimental setup



a) LDV
b) High-speed camera
c) Floodlight
d) Shaker
e) Beam
f) Transducer leads
g) Filter
h) DAQ
i) Shaker amp
j) Shaker F-Gen
k) Ultrasound P-R

Experimental setup



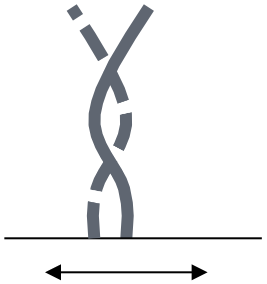


- Transducer pairs (front and back) ~100mm apart center to center ⟷
- Crack 50mm from transducer centers ⟷

Experimental setup

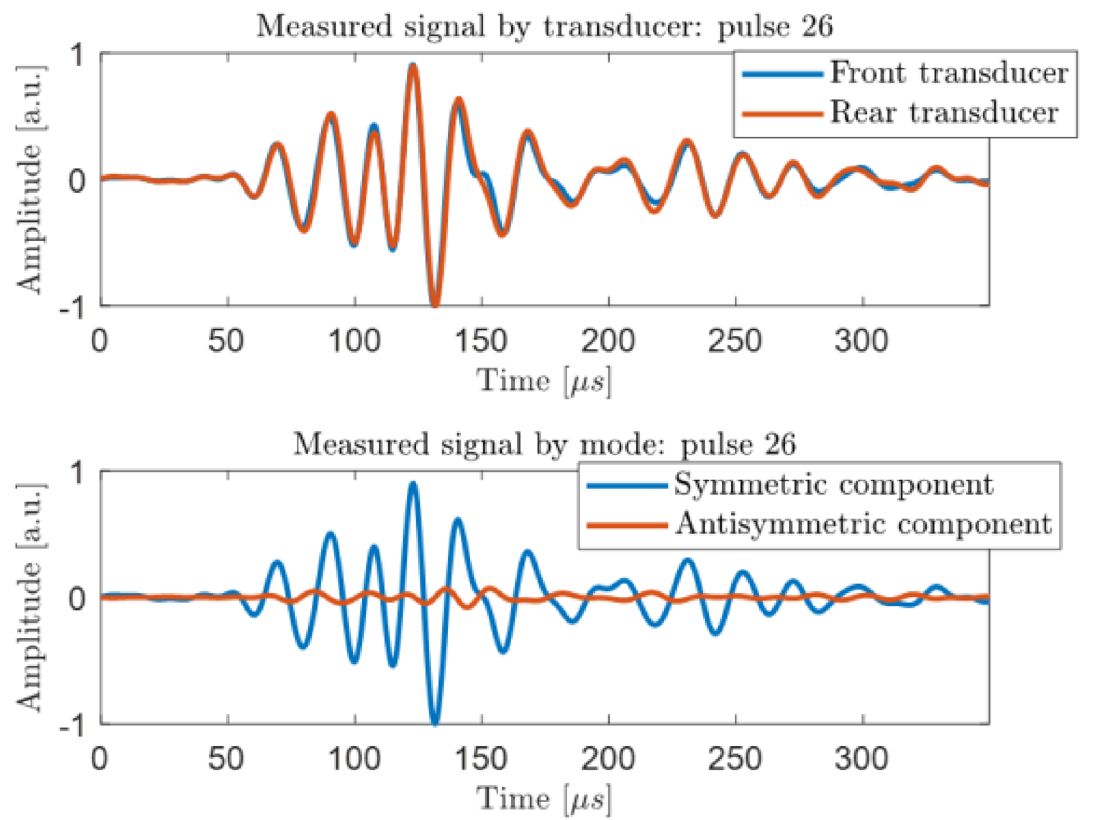
Testing protocol

- Three polycarbonate beams will be used
  - Healthy, cracked, and notched beam
- Beams will be driven in 2nd fixed-free mode
  - Notch/crack located near antinode
- Symmetric US guided wave as source
  - Easy to implement
- "Low" (~50kHz) frequency first-arrival used
  - Only S_0, A_0 modes propagate



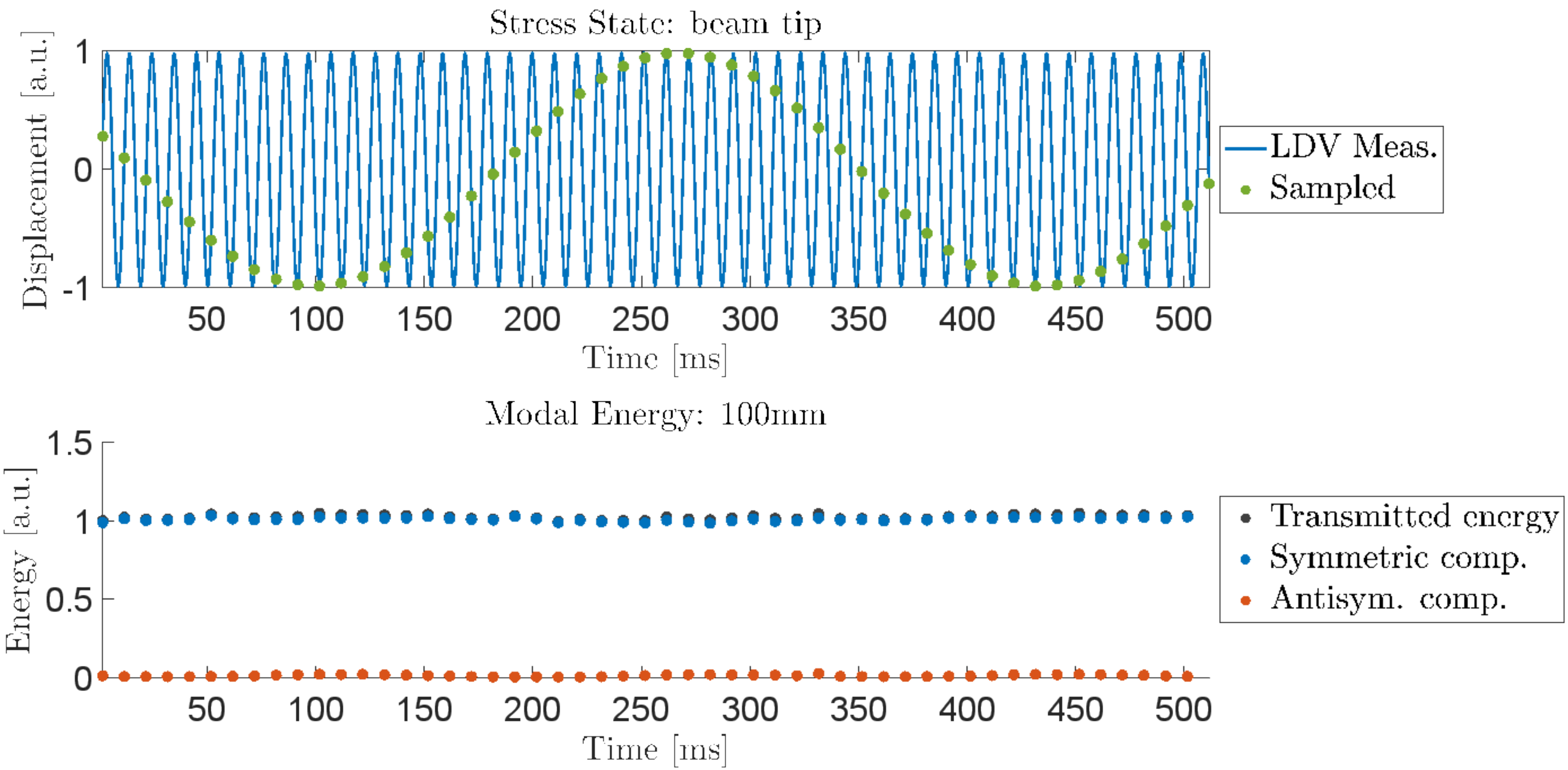
Processing

1. Measure full time-domain signals from transducers
2. Separate into individual US pulses
3. Window and filter
4. Extract symmetric and antisymmetric signals
5. Normalize by first measurement in test



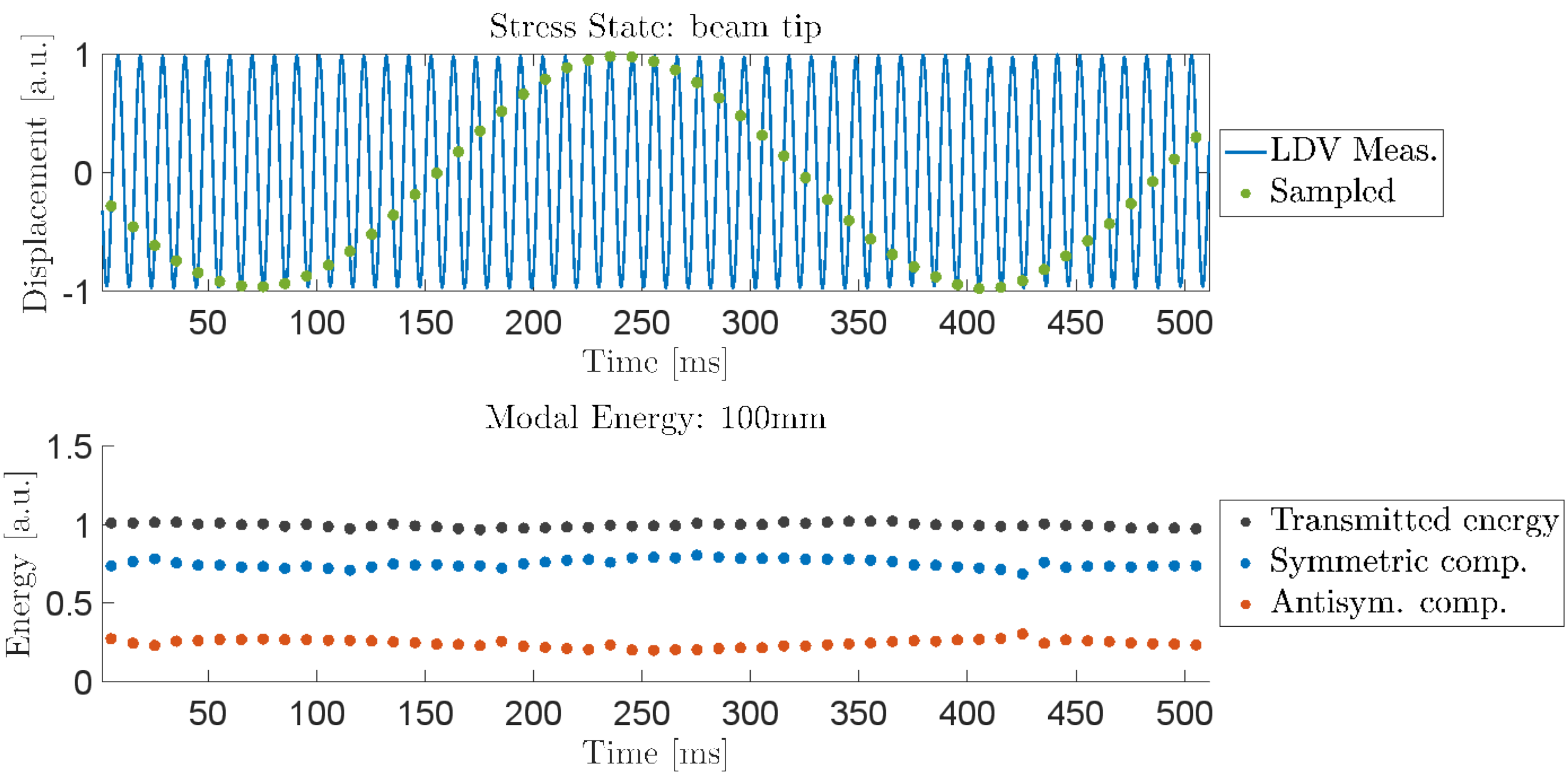
Experimental results

Results: healthy beam



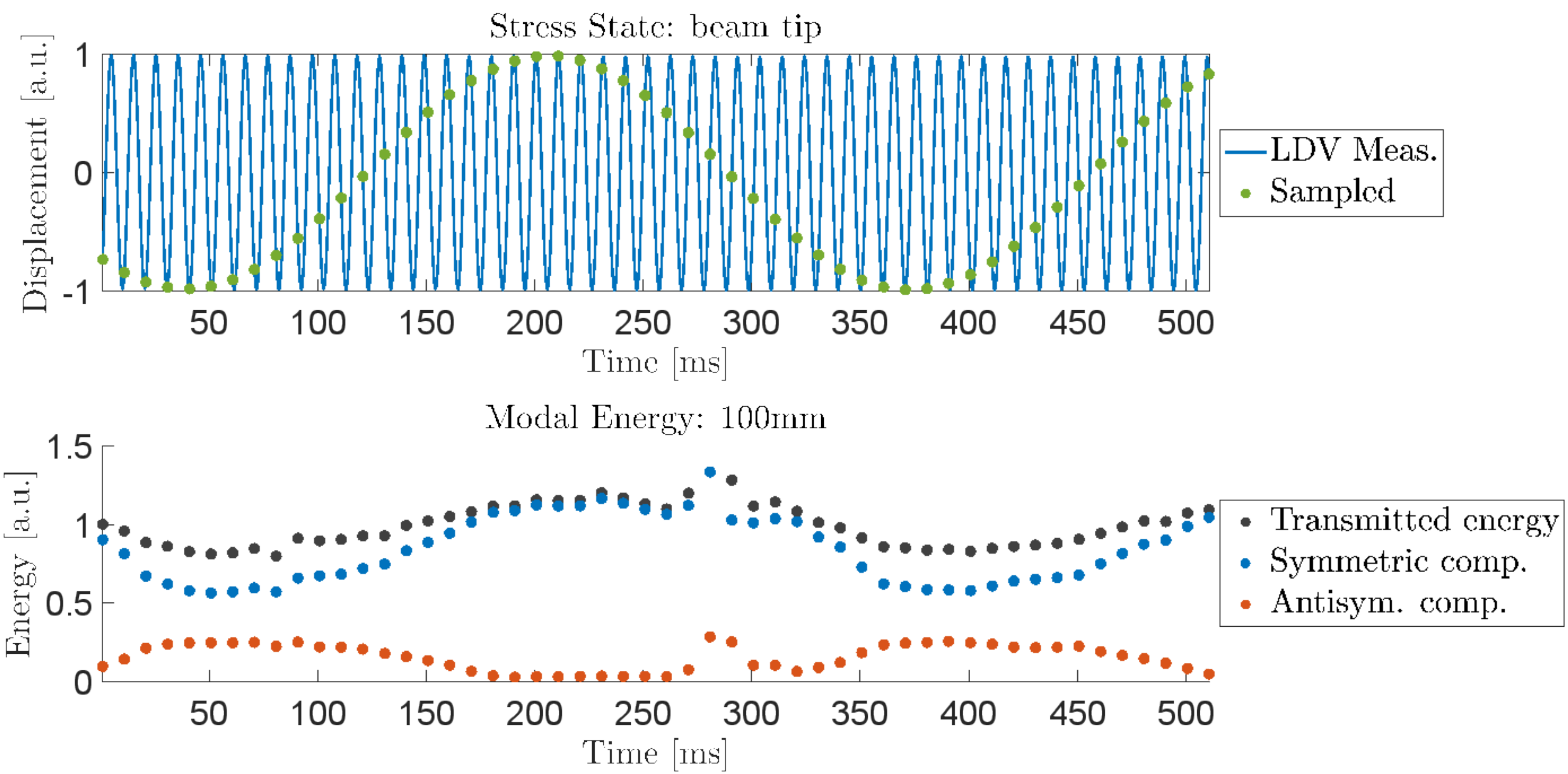
Experimental results

Results: notched beam



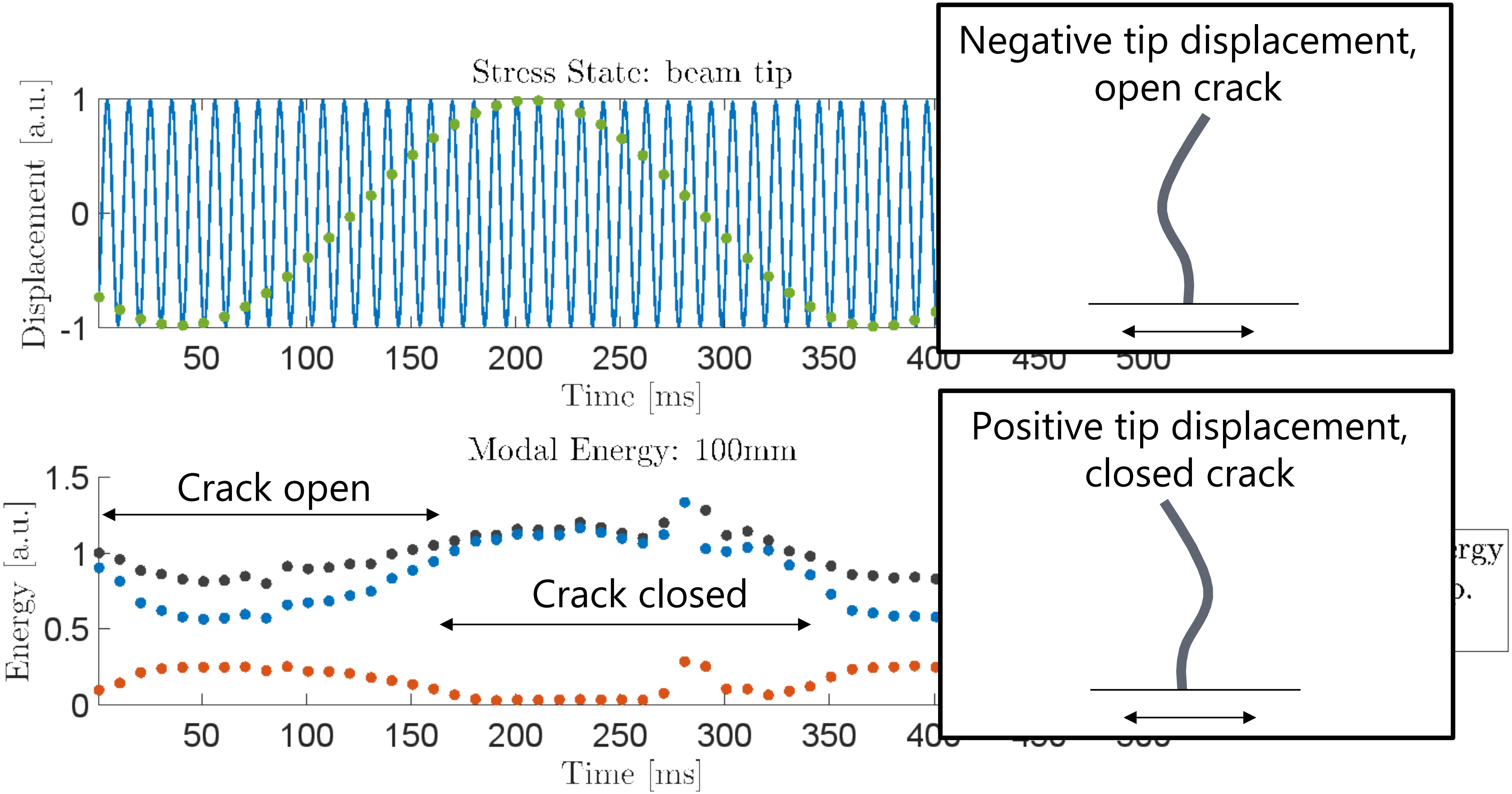
Experimental results

Results: cracked beam



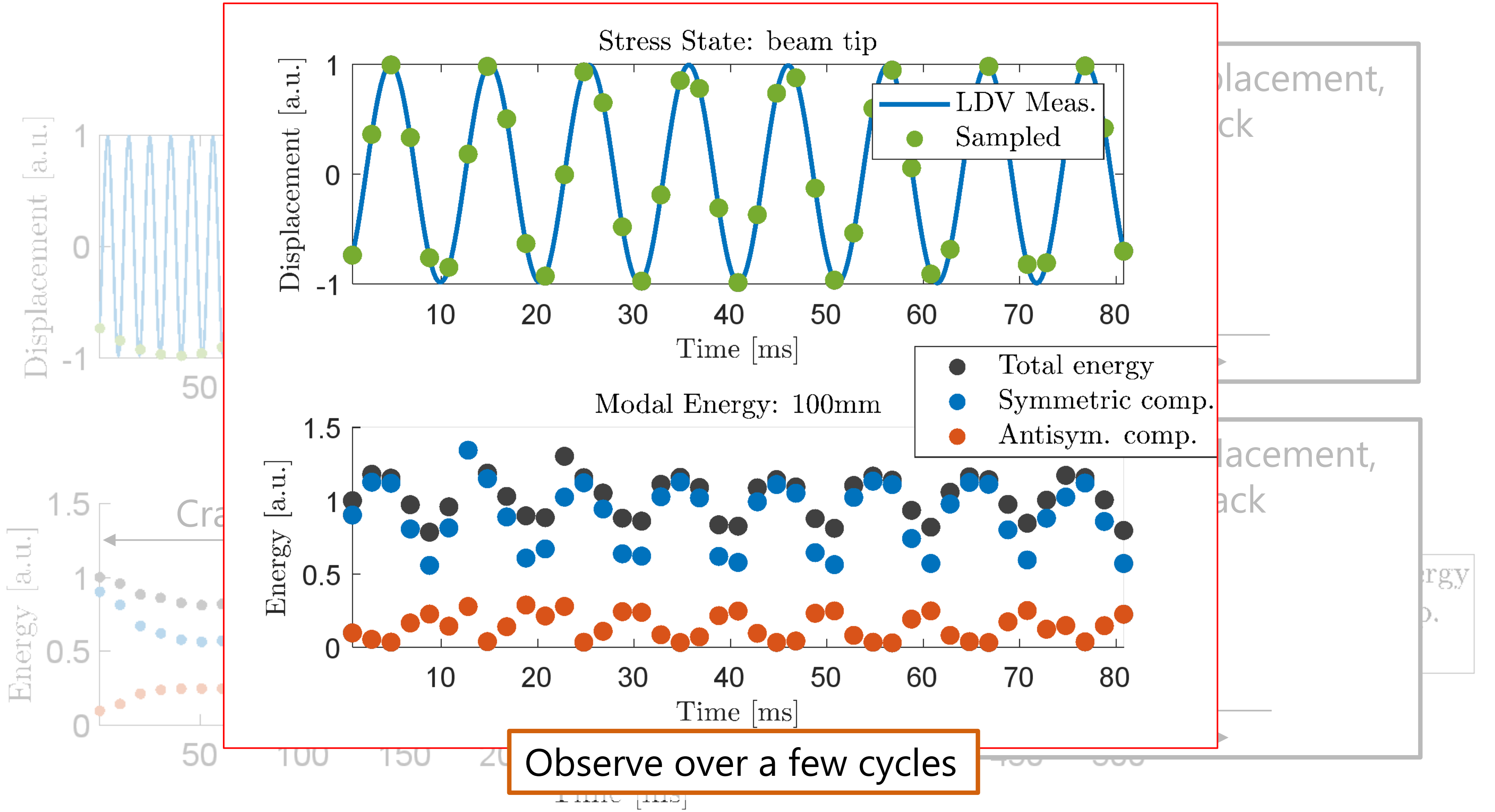
Experimental results

Results: cracked beam, agrees with predictions!



Experimental results

Results: cracked beam, agrees with predictions!



Observe over a few cycles

Applications of DATM

DATM has potential to be used as both a diagnostic tool and design methodology for complex plate structures

Diagnostic tool:

- Short-time scale: detect, locate, and characterize surface-breaking cracks
- Long-time scale: monitor growth of surface-breaking cracks
- Use of Lamb waves can allow for interrogation of built-up structures or hard-to-reach areas
- Local stiffness nonlinearity (crack) has instantaneously linear behavior when fully open or closed

Applications of DATM

DATM has potential to be used as both a diagnostic tool and design methodology for complex plate structures

Design methodology:

- Engineered defects: use cracks as subwavelength mode-converting scatterers
  - Hidden degree of freedom comes from time-varying (stress-state dependent) scattering behavior!
- Selective transmission: spatiotemporal modulation can induce probe scattering behavior than depends on the pump frequency
- Semi-analytical methods can be used for quick exploration of design space (in progress)