

Structural Health Monitoring in Composite Materials using Frequency Response Methods

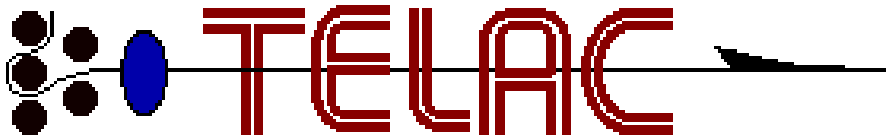
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Structural Health Monitoring

- **Definition:** SHM denotes a system with the ability to detect and interpret adverse “*changes*” in a structure in order to improve reliability and reduce life-cycle costs.
- Can be implemented many ways
 - active/passive
 - post-operation/in-situ
- Reduces inspection and maintenance expenses and increases the reliability of damage detection and failure prediction
 - currently 27% of aircraft life cycle cost is spent in inspections
 - avoid tear-down of built up structures for required inspections
 - much of the airline and military fleet are aging aircrafts, fatigue and corrosion become a problem

Overall Research Goals

- Status quo of SHM research
 - several projects investigating particular methods on ideal coupons
 - investigators are often over-sold on their own detection method
 - little presented on limitations of methods or pertinence to SHM
- Proposed research
 - investigate potential sensing methods and combinations
 - report on strengths and limitations of methods
 - implementation potential for a real structure (conformability, size, etc.)
 - show progression of detection reliability through building block
- Focus on composite materials — high pay-off area
 - easy to adhere or embed, can tailor material to suit needs
 - practical for new programs, can help to relax fears of “BVID”

Approach

- Review literature for candidate damage detection methods
- Build analytical models
 - determine theoretical sensitivity of method
 - address sensor placement
 - assist in design of experiments
- Experimental verification
 - test simple specimens with various damage, work up through building block stages to structural element level
 - assess feasibility of implementing method in a SHM system
- System architecture
 - sensor integration
 - test samples with realistic sensors
 - test method on representative structures

Frequency Response Methods

- Literature review
 - among the most common health monitoring techniques
 - simple, flexible and inexpensive to implement (cost, weight, power)
 - global in nature, can scale easily
 - lacks ability to detect small damage and requires large data storage
 - actuation between 10-20 kHz is optimal for structural response, however often impractical to collect data over 2 kHz
- Valdes and Soutis (Imperial) used piezo-ceramic patches to detect delamination in rectangular composite coupons
 - frequency sweeps up to 15 kHz used to induce dynamic response
 - linear reduction in natural frequency as delamination area increased
 - not model-dependent

Changes in Frequency Response

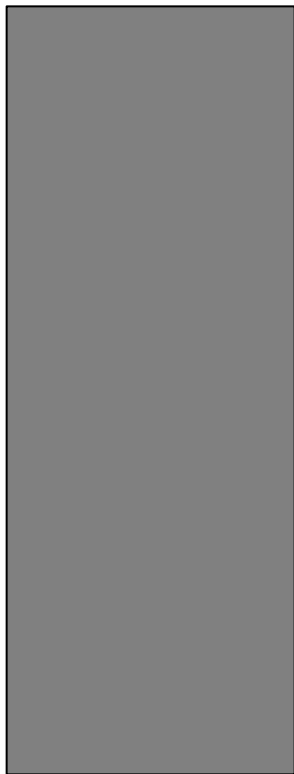
- Natural frequencies for beams: $\omega \propto \sqrt{\frac{EI}{m}}$ and $\omega \propto \sqrt{\frac{Et^2}{I}}$
 - stiffness reduction decreases ω
 - density/mass reduction increases ω
 - boundary conditions most directly affect ω
- Mode shapes are altered by damage locations
 - bending modes affected by damage near nodes
 - torsion modes affected more by asymmetric damage
 - bending and torsion modes begin to couple
- Response amplitude increases with more damage

FE Modal Analysis

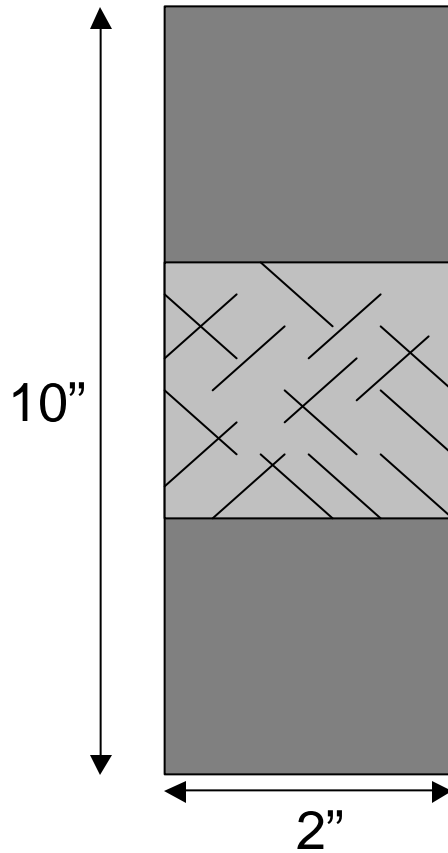
- Clamped-free rectangular slender plate
- Modeled and processed in I-DEAS
 - 10x2” quasi-isotropic laminate (ABD matrices calculated in Matlab)
 - 2000 0.2” square shell elements
 - solved for all modes 0-20 kHz
 - mode shapes and transfer functions inspected in post-processor
- Several models representing various damage types
 - delamination — 2 layers of half laminate elements in damage region
 - fatigue cracks — 20% reduction in E of region (Tong et al., 1997)
 - fiber fracture — 10% reduction in E of region (Whitney, 1999)
 - hole — physically modeled holes in various locations

Simulated Damage Modes

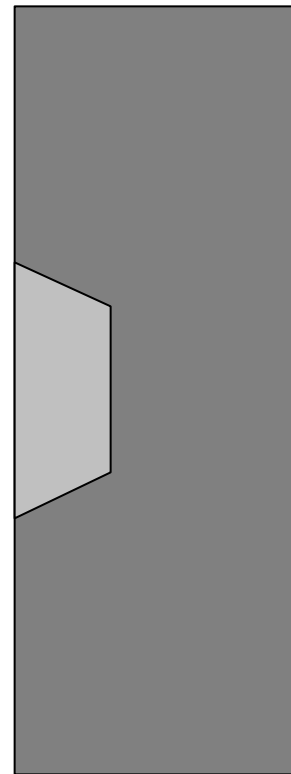
Control Specimen



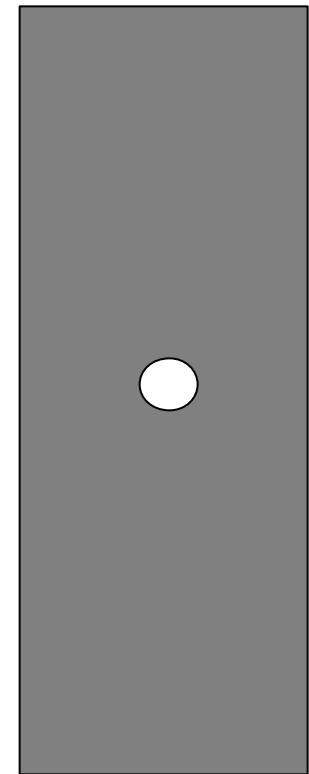
Matrix Crack Specimen



Delamination Specimen

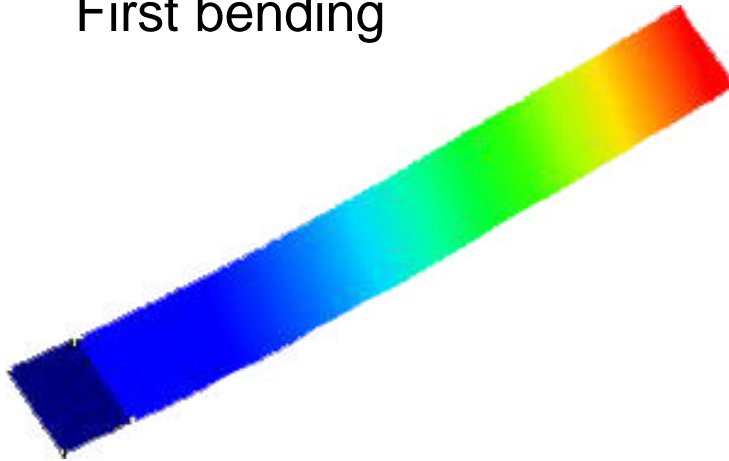


Core Drilled Specimen

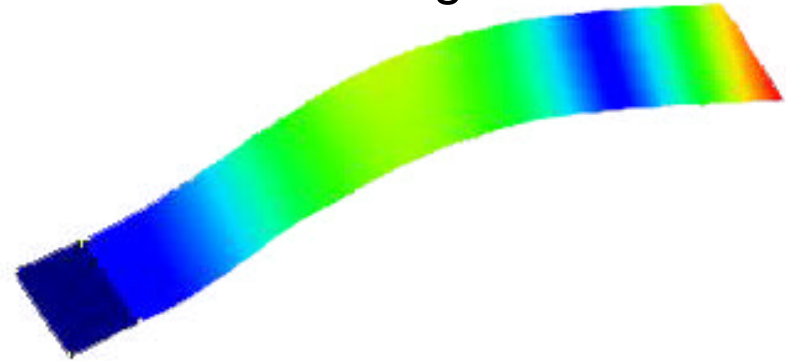


FEA Mode Shapes

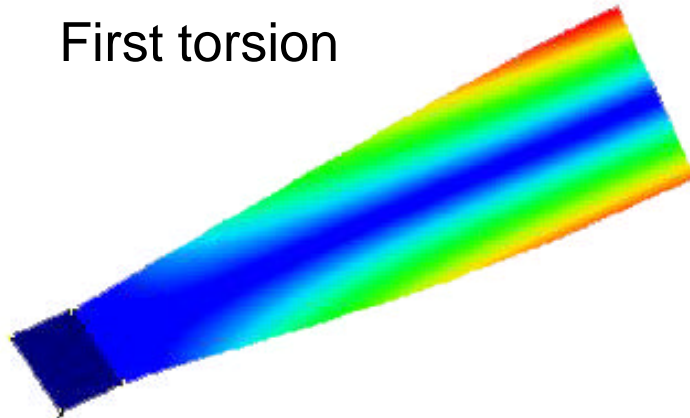
First bending



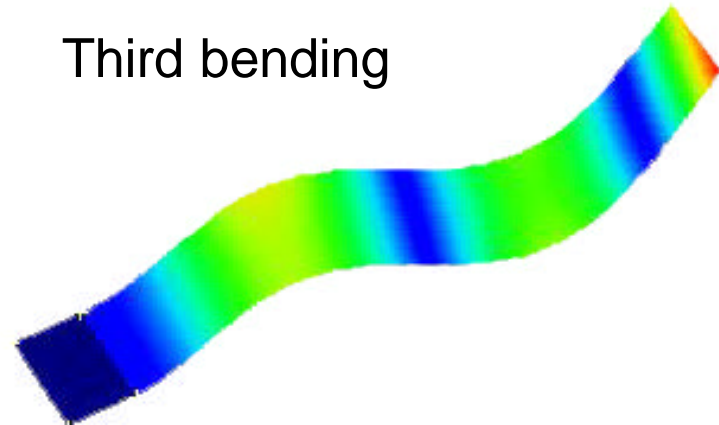
Second bending



First torsion

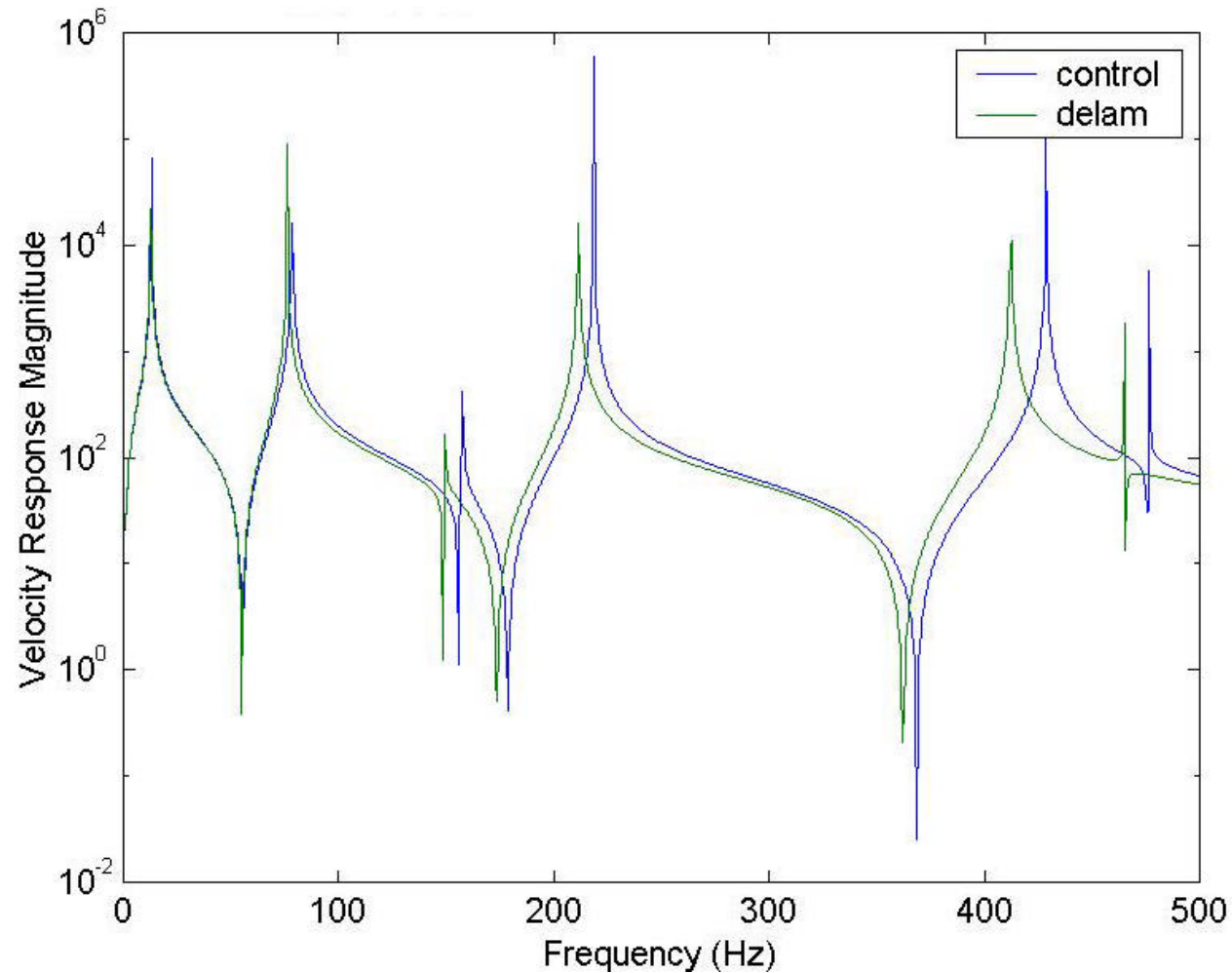


Third bending



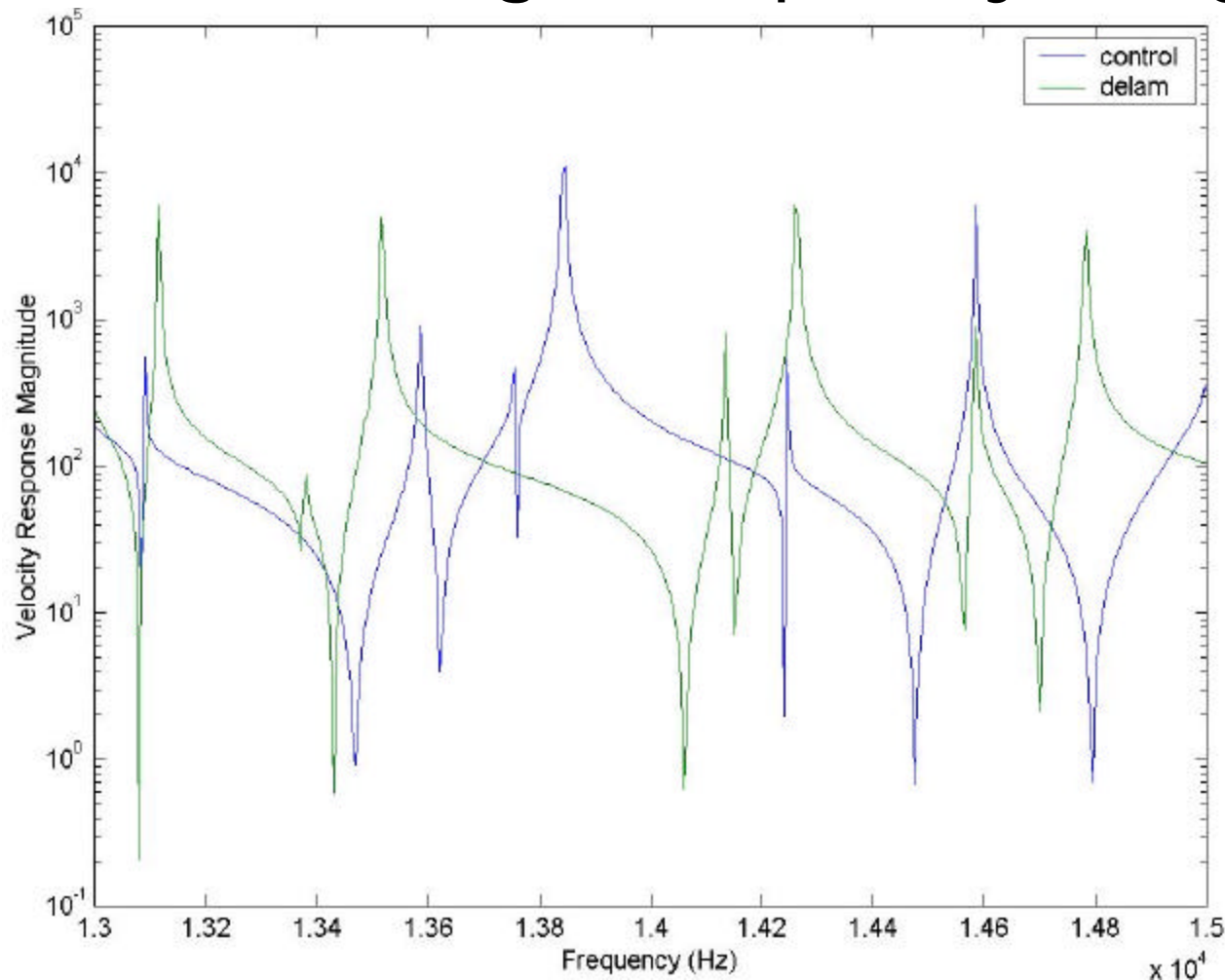
First four mode shapes of control specimen plotted in I-DEAS post-processor

Transfer Function Response Predicted Low Frequency Range



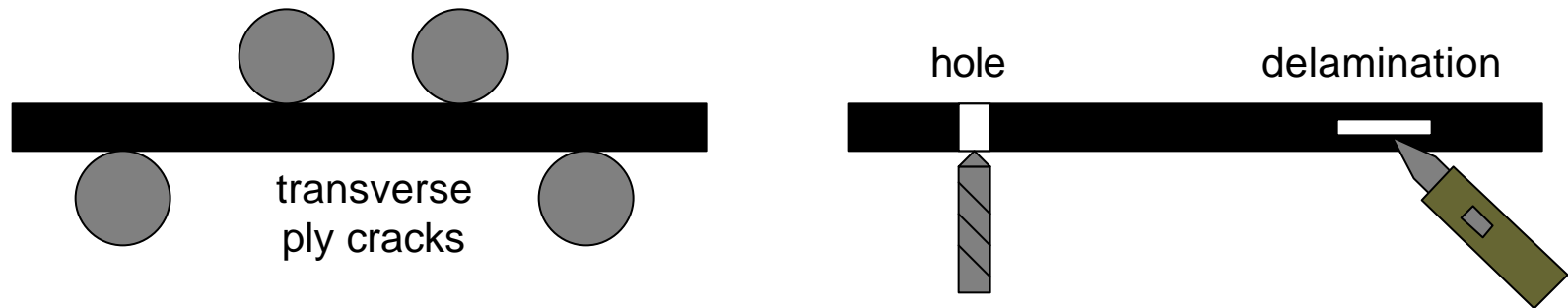
Frequency response plot demonstrates shift in frequencies due to delamination

Transfer Function Response Predicted High Frequency Range



Shifted peaks are difficult to match with control model at high frequencies

Experimental Approach



- AS4/3501-6 quasi-isotropic [90/? 45/0]s laminates
- Introduced representative damage to composite specimens
 - delamination — slice utility knife in side of sample, or teflon strip
 - transverse ply cracks — 4-pt fatigue on center of specimen
 - fiber fracture — 4-pt bend until audible damage
 - stress concentration — drilled hole through specimen
 - impact — hammer struck against steel plate in center of sample
- X-radiography used to verify damage

X-Ray Damage Verification

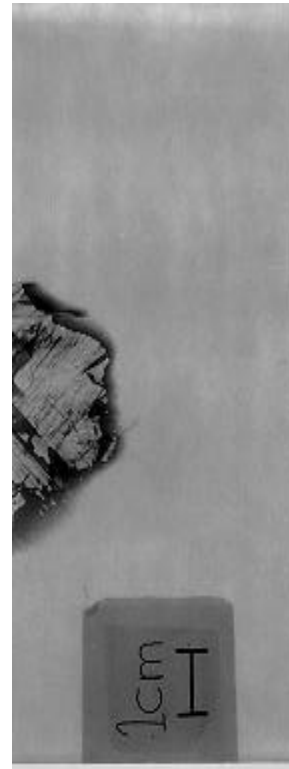
Control Specimen



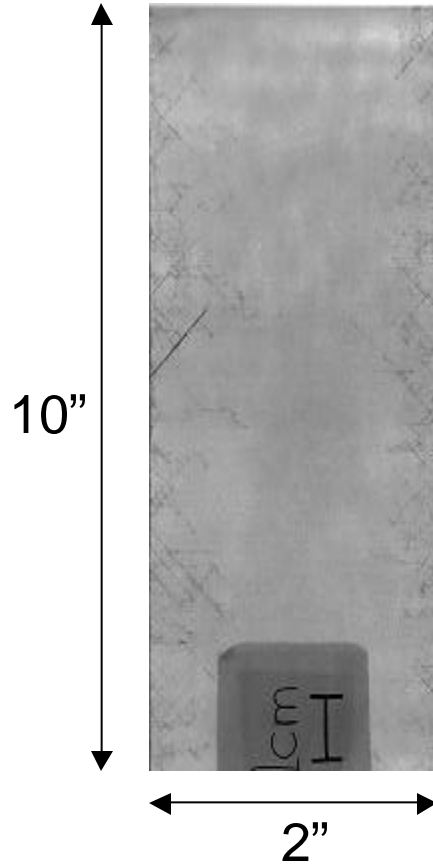
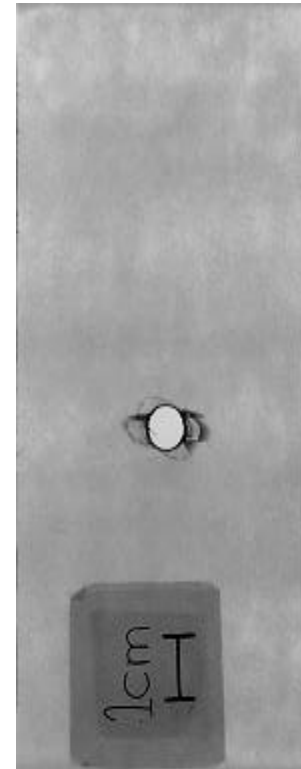
Matrix Crack Specimen



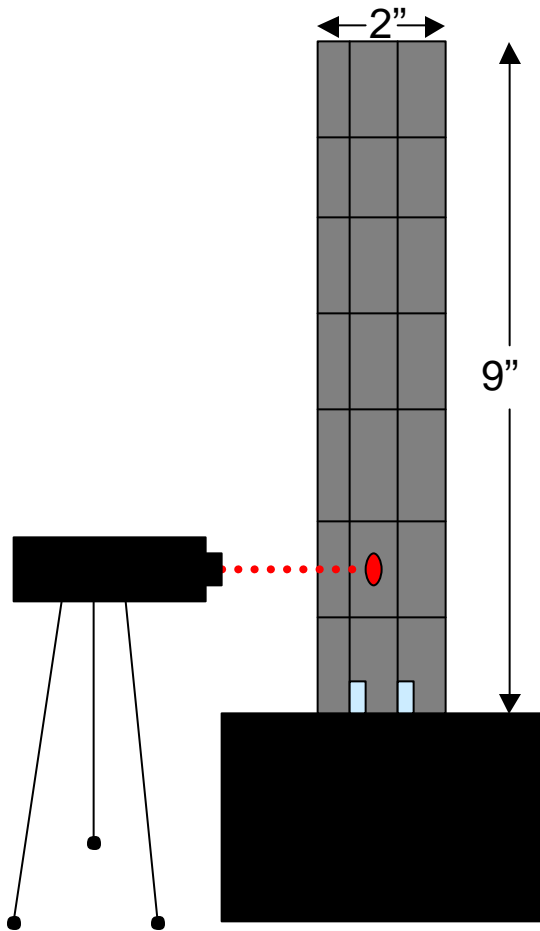
Delamination Specimen



Core Drilled Specimen

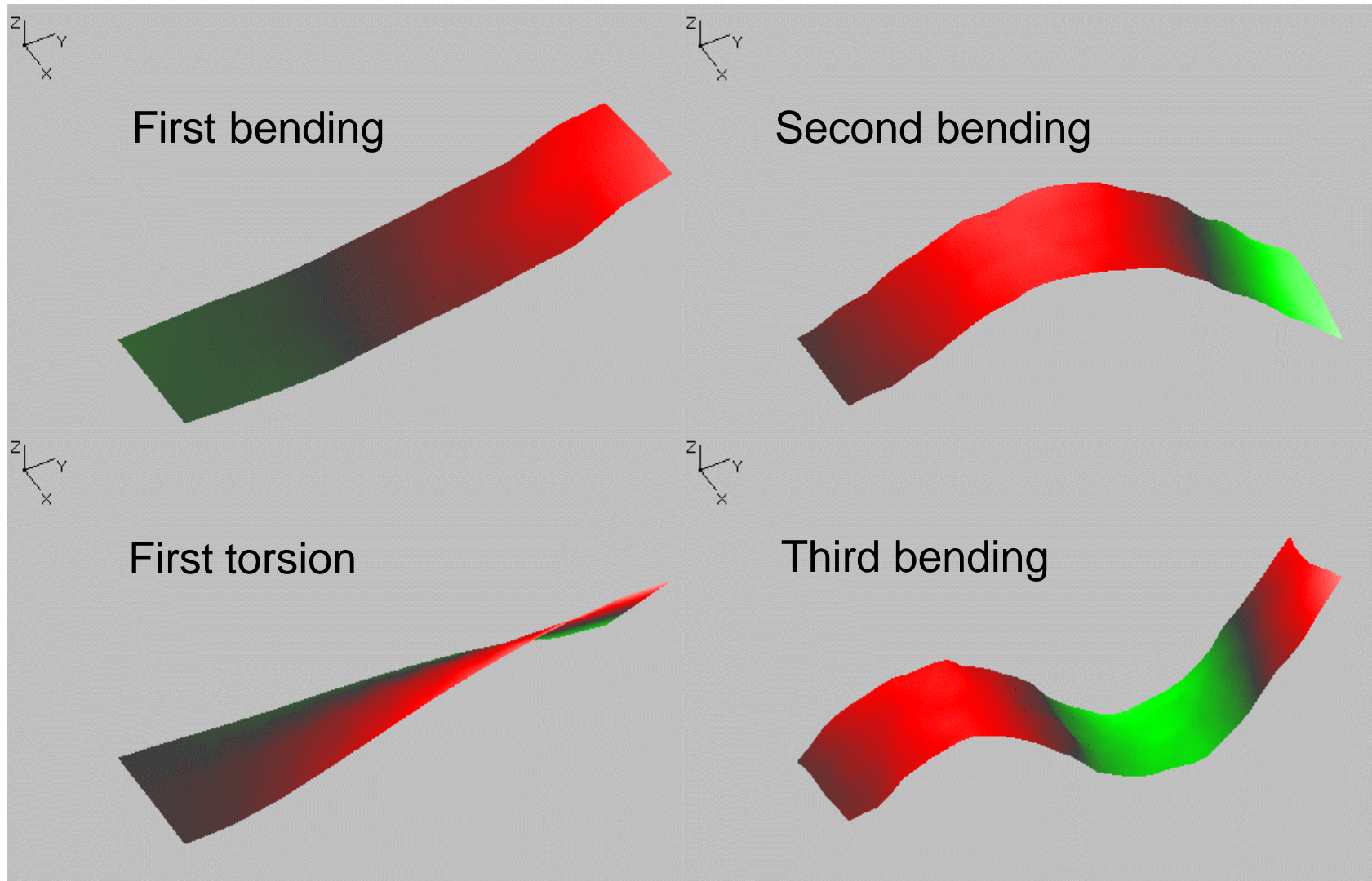


Experimental Methods



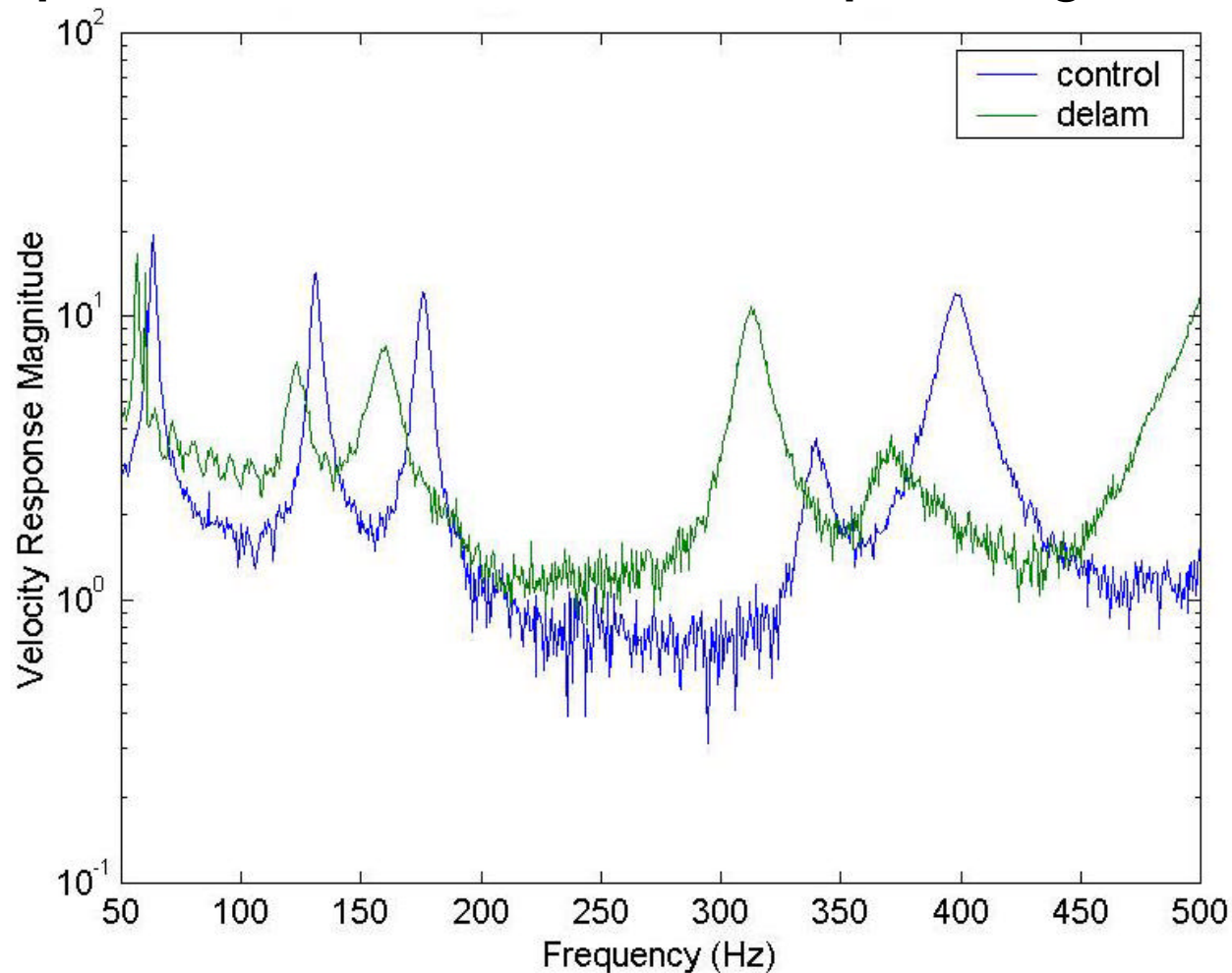
- Scanning laser vibrometer tests
 - 3 samples of each type tested
 - clamp boundary condition simulated by a vice tightened with a torque wrench
 - 2 piezoceramics at base driven out of phase with 8V sine sweep signal to excite resonance
 - velocity response measured at mesh grid points with laser interferometer
 - plotted response averaged across grid
- Impedance analyzer tests
 - identical specimen and set-up
 - one piezoceramic actuates, other senses
 - potential for implementation in SHM system
 - lacks mode shape information
 - good correlation with vibrometer results

Experimental Mode Shapes



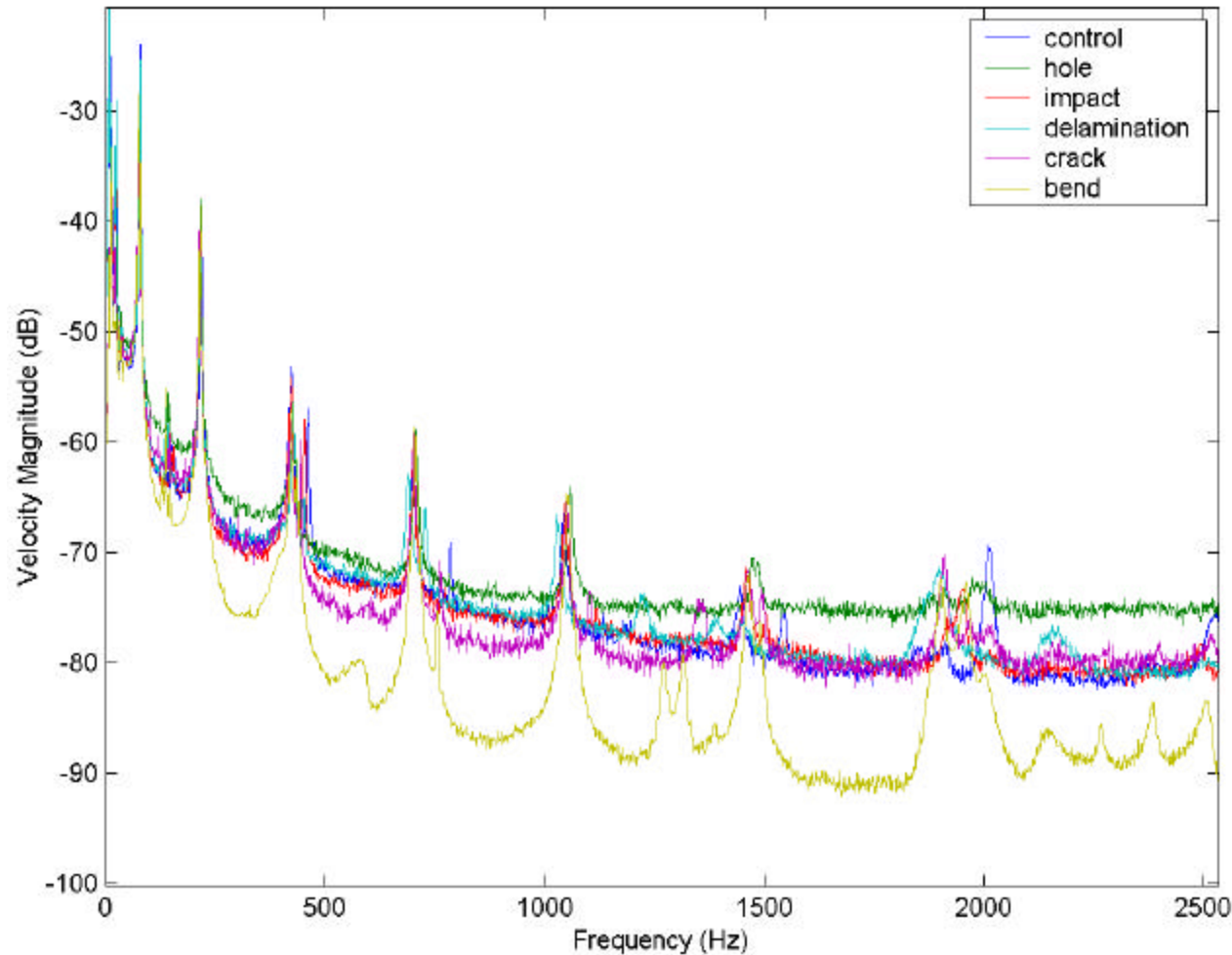
Mode shapes of control specimen from vibrometer data matches FEA results

Averaged Velocity Response Experimental Low Frequency Range



Clearly identifiable shift in frequencies due to delamination

Averaged Velocity Response Experimental Low Frequency Range



All damage caused a small reduction in frequencies, various modes affected differently

Frequency Comparison

Shape	(All Hz)	Control	Hole	Impact	Delam	Crack	Fracture
Mode 1: 1 st Bending	FEA	12.5	12.4	12.5	12.1	12.1	12.4
	Experiment	12.5	12.5	12.5	12.5	12.5	12.5
Mode 2: 2 nd Bending	FEA	77.8	77.2	77.5	75.5	73.7	76.3
	Experiment	78.1	78.1	76.5	78.1	75.0	76.3
Mode 3: 1 st Torsion	FEA	157	155	156	149	150	154
	Experiment	157	148	147	137	146	137
Mode 4: 3 rd Bending	FEA	218	217	217	211	213	216
	Experiment	218	217	216	215	209	214
Mode 5: 4 th Bending	FEA	428	425	426	412	413	422
	Experiment	423	423	423	428	413	423
Mode 6: 2 nd Torsion	FEA	476	473	474	465	466	472
	Experiment	461	453	453	451	428	432

Frequency Comparison

Shape	(All Hz)	Control	Hole	Impact	Delam	Crack	Fracture
Mode 1: 1 st Bending	FEA						
	Experiment	0.0%	0.8%	0.0%	3.3%	3.3%	0.8%
Mode 2: 2 nd Bending	FEA						
	Experiment	0.4%	1.2%	1.3%	3.4%	1.8%	0.0%
Mode 3: 1 st Torsion	FEA						
	Experiment	0.0%	4.5%	5.8%	8.1%	2.7%	4.5%
Mode 4: 3 rd Bending	FEA						
	Experiment	0.0%	0.0%	0.5%	1.9%	1.9%	0.9%
Mode 5: 4 th Bending	FEA						
	Experiment	1.2%	0.5%	0.7%	3.9%	0.0%	0.2%
Mode 6: 2 nd Torsion	FEA						
	Experiment	3.2%	4.2%	4.4%	3.0%	8.2%	8.5%

Good correlation between FEA and experimental results at frequencies < 500 Hz

Frequency Comparison

Shape	(All Hz)	Control	Hole	Impact	Delam	Crack	Fracture
Mode 1: 1 st Bending	FEA	12.5	-0.1	0.0	-0.4	-0.4	-0.1
	Experiment						
Mode 2: 2 nd Bending	FEA	77.8	-0.6	-0.3	-2.3	-4.1	-1.5
	Experiment						
Mode 3: 1 st Torsion	FEA	157	-2.0	-1.0	-8.0	-7.0	-3.0
	Experiment						
Mode 4: 3 rd Bending	FEA	218	-1.0	-1.0	-7.0	-5.0	-2.0
	Experiment						
Mode 5: 4 th Bending	FEA	428	-3.0	-2.0	-16	-15	-6.0
	Experiment						
Mode 6: 2 nd Torsion	FEA	476	-3.0	-2.0	-11	-10	-4.0
	Experiment						

Small differences between control and damaged models at frequencies < 500 Hz

Modal Analysis Conclusions

- Method shows useful detection sensitivity to damage
- Experiments are very sensitive to boundary conditions
- Low frequency response shows little change in characteristics
- High frequency response not straightforward to interpret
 - little information on damage type or location (cracks ? 2" delam)
 - modes shapes combine, new local modes can appear
 - altering one variable linearly is not practical for real applications
- Possible strategy for implementation in SHM system
 - advantages: light, conformal, can be passive, variety of sensors
 - first line of defense for detecting changes caused by damage, use of active sensors for more detail
 - last line of defense for widespread fatigue or aging damage on global modes; can set limit on modal resonance change

Future Recommended Research

- Similar study for other potential detection methods
 - lamb wave
 - eddy current
 - acoustic emission
- SHM components
 - communication between sensors and processing unit
 - data acquisition, processing and power requirements
- Test on representative structures
 - built up fuselage section or helicopter blade
 - use realistic sensors
 - test in service environment, noise and vibrations
- Experiment with system architecture
 - improve reliability with multiple sensing method scheme
 - implement SHM system with all components