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Wood Joint Design Toward Structural Robustness

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Requirements

- Ductility
- Energy Dissipation Capacity

  under dynamic loading

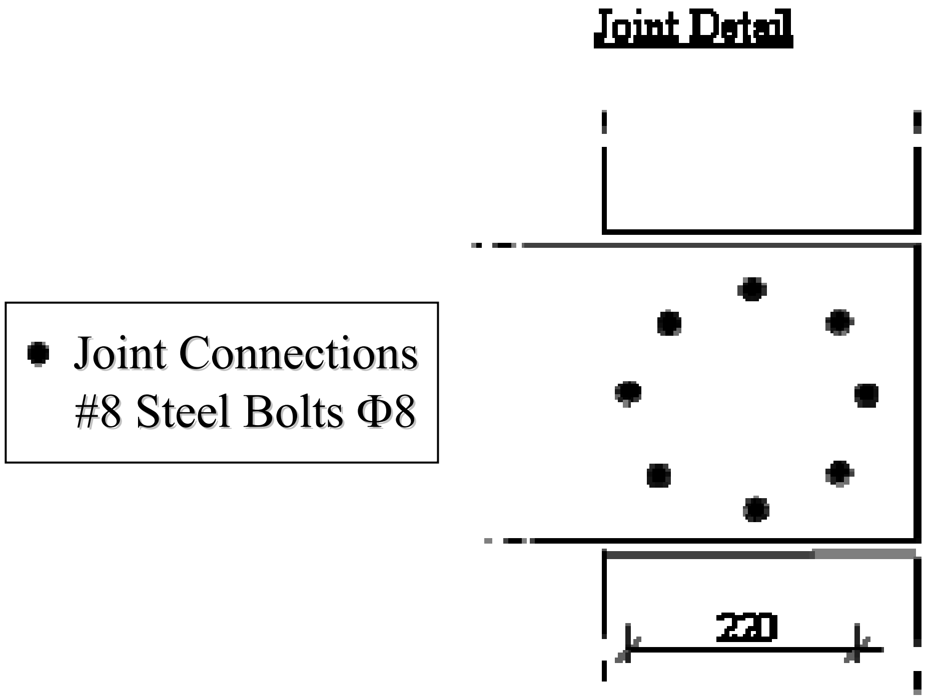
Smart Joint Design

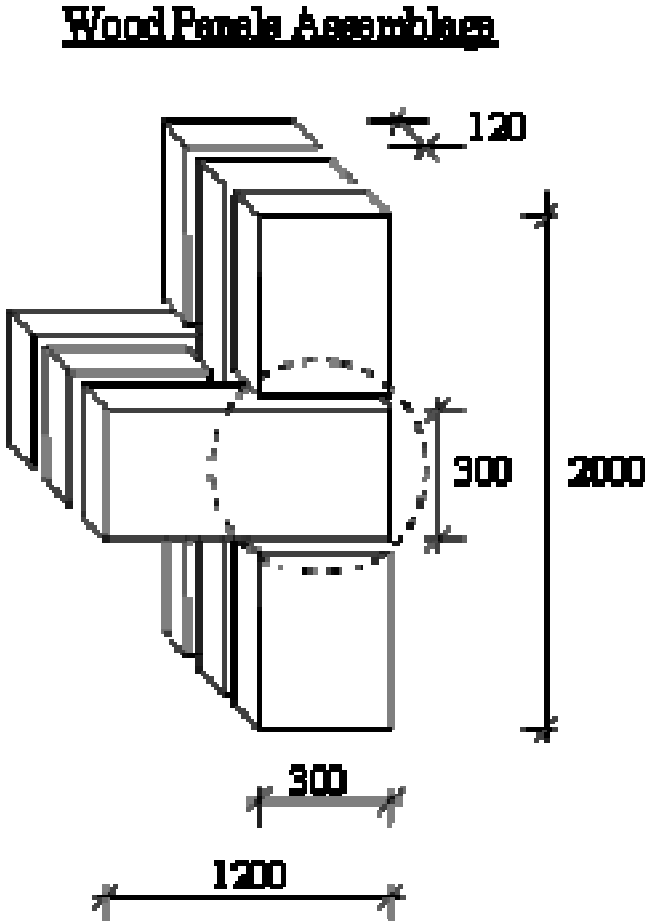
- It prevents the relative displacements of the members under standard operating mode;

- But it dissipates energy by allowing the relative displacements, when a certain acceleration level is triggered.

Test Setup

- Physical Model Design & Geometry





Test Setup

- Shaking Table

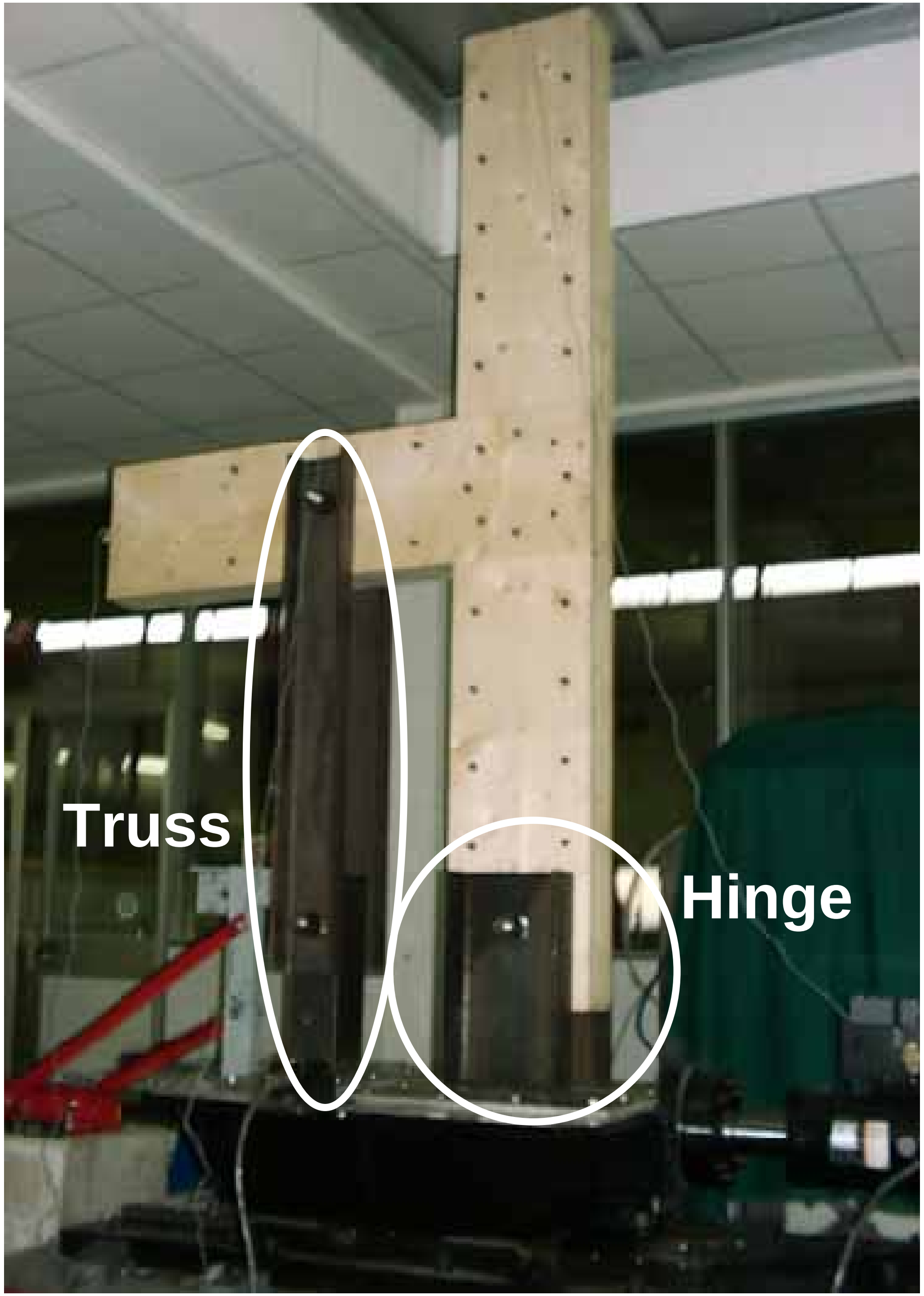
Dimensions	92 × 92 cm
Table Mass	150 kg
Steel Reaction Mass	7 tons
Concrete Support Mass	15 tons
Maximum Displacement	+/- 75 mm
Maximum Velocity	120 cm/sec
Maximum Acceleration	4 g
Operational Frequency Range	0 – 25 Hz
Natural Frequency	27 Hz

Test Setup

- Steel Connections

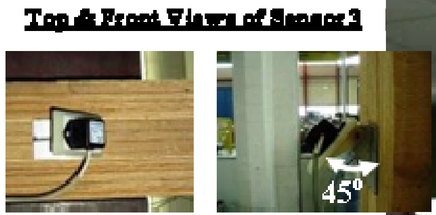
- Transfer the dynamic loads to the model

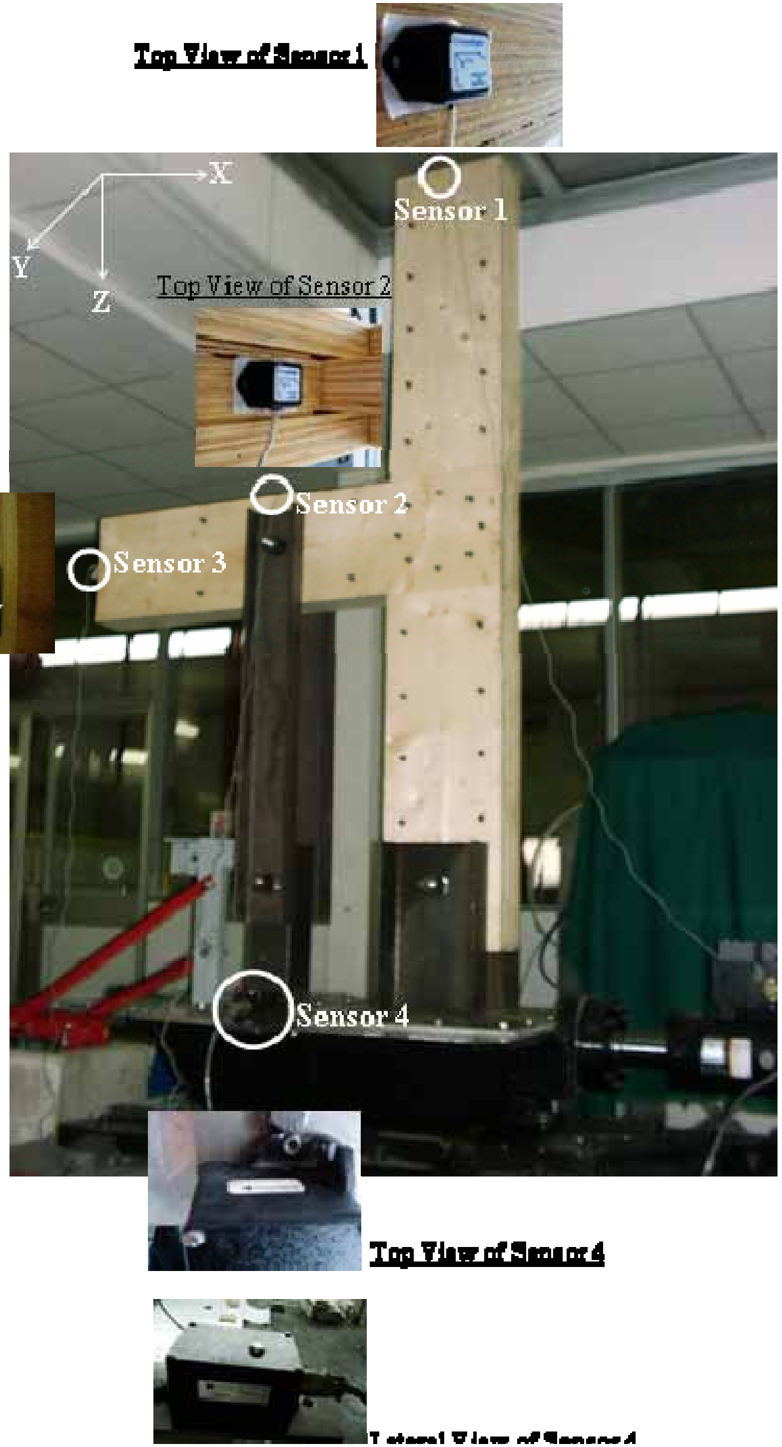
- Simulate the boundary conditions



Test Setup

- Monitoring System





Sensor	Location	Type
1	Vertical Members Middle Top	Crossbow CXL01LF3
2	Horizontal Members Middle Top	–
3	Horizontal Members Left Edge @ 45° on the *XZ* plane	–
4	Shaking Table	Kinemetrics FBA-11

Test Setup

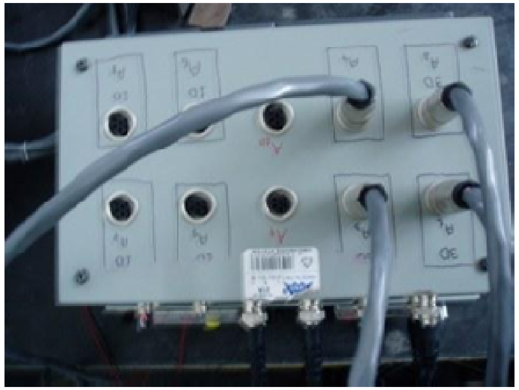
- Accelerometers

	Crossbow (3D) CXL01LF3	Kinemetrix (1D) FBA-11
Input range [g]	±1	±1
Span output [V]	±2±0.1	±2.5 (in 10000 Ω)
Sensitivity [V/g]	total 2 (1 x amplitude)	total 2.5 (1.25 x amplitude)
Frequency range [Hz]	max 125	Max 50
Transverse sensitivity [%]	±3.5	±3
Non-linearity [%]	±3	±1
Temperature range [°C]	(-40,+85)	(-20,+70)
Supply current [mA]	12	2.5
Supply voltage [V]	(+8,+30)	12

Test Setup

- Acquisition System

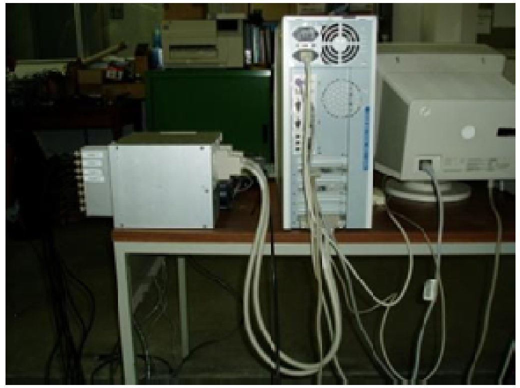
Sensor	Monitored Directions	Channel
1	X Y	0 1
2	X Y	2 3
3	45° X Y 45° Z	4 5 6
4	-X	7



a) Junction box top view:
4 inputs from the sensors

b) Junction box lateral view:
8 outputs to the acquisition

c) 8 Channels acquisition system
(anti-aliasing filter @ 20 Hz)



d) Link to processing unit
(A/D converter & data storage)

Note: Channels 4 and 6 are combined together to evaluate the corresponding horizontal (along X) and vertical (along Z) acceleration components, which will be denoted as Channels 4* and 6*, respectively.

Test Setup

- Tested Configurations
- Test N is performed only to check the actual ability of the horizontal and vertical members to undergo relative displacements.
- Tests A, B, C are carried out in both

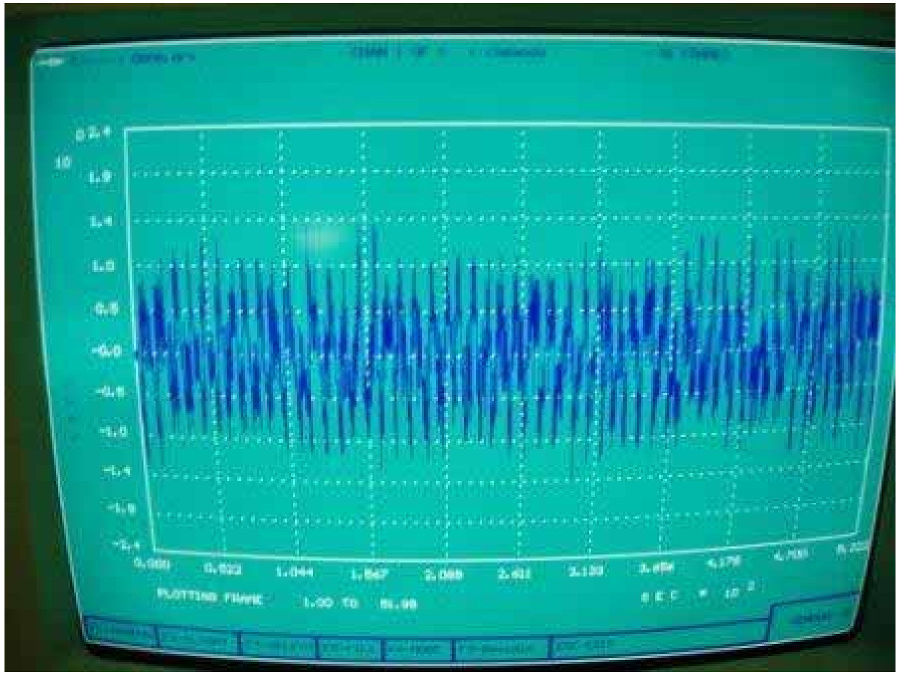
- Friction mode (tightly fastened bolts)
  → Tests A_F, B_F, C_F
- Shear mode (loosened bolts)
  → Tests A_S, B_S, C_S,

Test	Joint Connections
N	None
A	8 Steel Bolts Φ8
B	2 Steel Bolts Φ8 in the Horizontal Direction
C	2 Steel Bolts Φ8 in the Vertical Direction

Dynamic System Identification

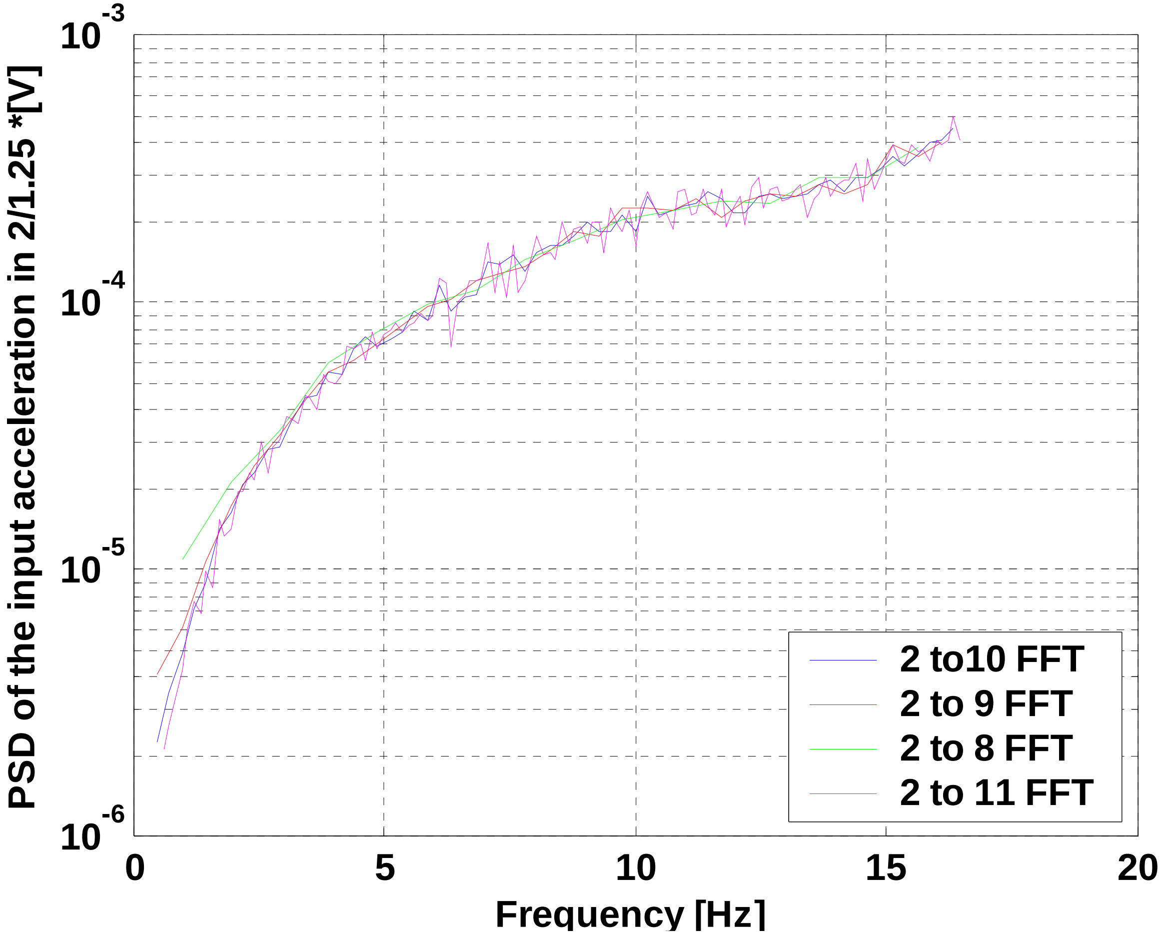
- Input Signal (Excitation)

displacement time history of duration 5 min, whose corresponding acceleration values fit a white noise spectrum in the frequency range from 0 to 20 Hz



Dynamic System Identification

- PSD of the Base Acceleration (Channel 7, Sensor 4)



- Constant only between 10 and 12 Hz;
- It decreases for lower frequencies, due to the significant weight of the model;
- It increases for higher frequencies, because of the shaking table resonant phenomena.

→ The table does not completely follow the driving input signal.

Dynamic System Identification

- Frequency Response Analyses

  - the first 2^{12} points are removed from the recorded signals to eliminate the initial effects;

  - 2^{16} points are retained for the subsequent data analyses;

  - a smoothed FFT is obtained by averaging over signal windows of different lengths;

  - the signal windows of 2^{9} points provide the best compromise between accuracy and regularity, and it will be therefore adopted in the following.

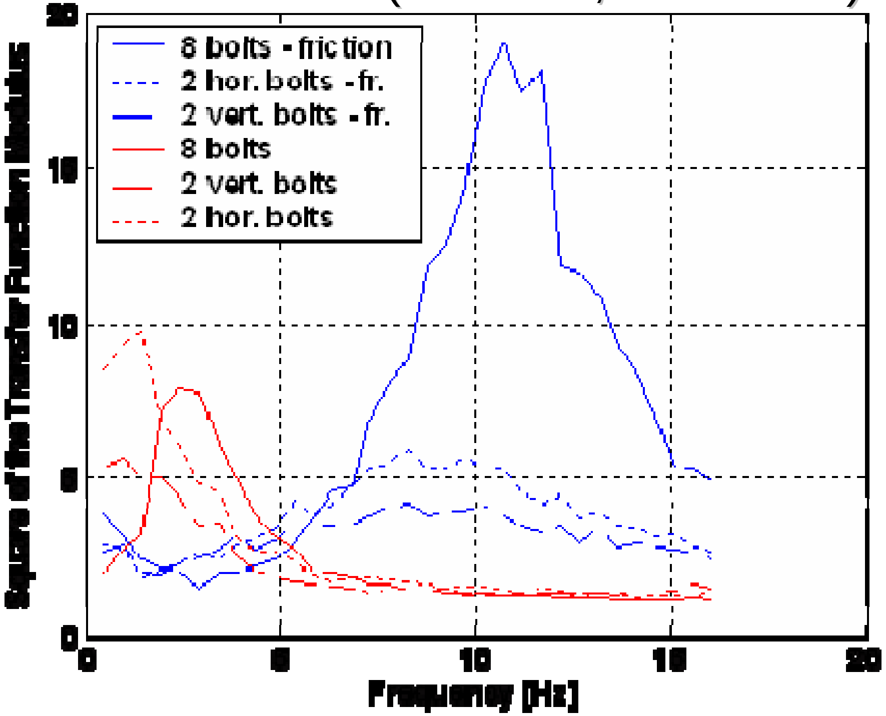
Dynamic System Identification

- Transfer Functions

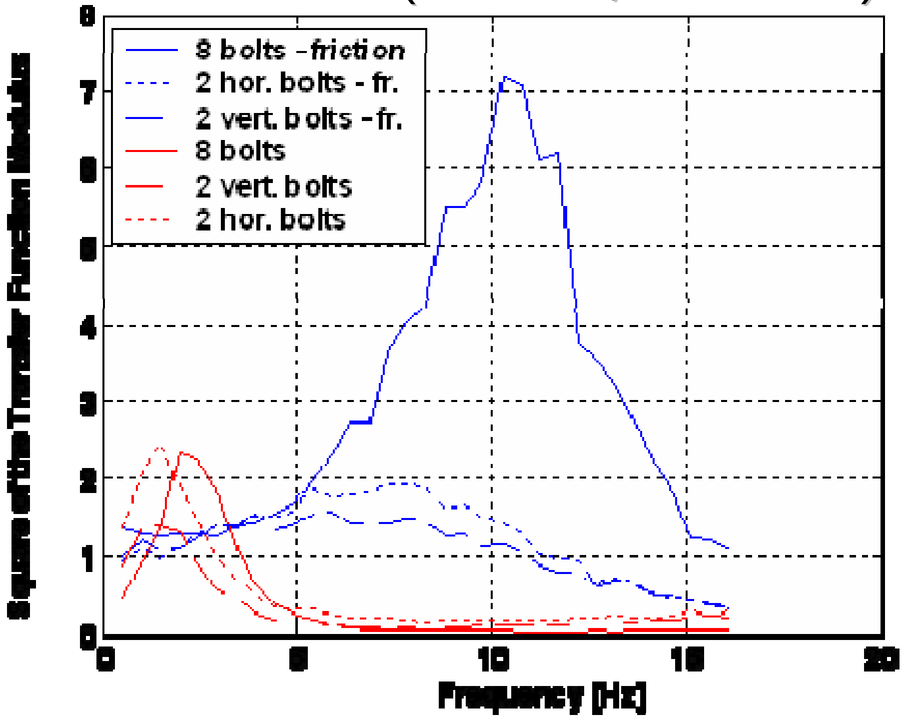
  squared modulus = ratio PSD(Channel i) / PSD(Channel 7), i = 0,1,2,…,6

- Longitudinal Accelerations

Channel i = 0 (Sensor 1, X direction)



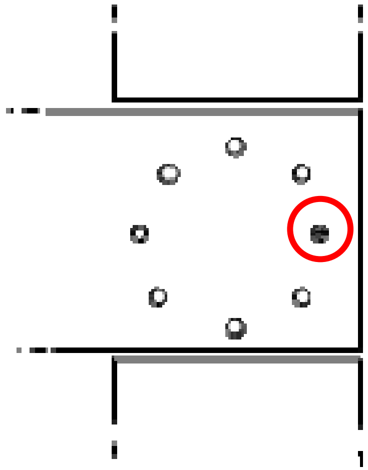
Channel i = 2 (Sensor 2, X direction)



Testing Different Solutions for a Smart Joint Design

- From the previous studies, it is evident that removing some bolts provides larger damping values, without transferring energy to the transversal motion.
- Therefore, during a dynamic excitation, the relative displacements can be increased, without loss of global stability, in order to shift the main natural frequency of the system far from those of the external input.
- For this purpose, a semi-active control scheme can be adopted.
- Different solutions are tested by replacing the steel bolts with a single bar of reduced diameter and of various material, at the joint location.

Testing Different Solutions for a Semi-Active Joint

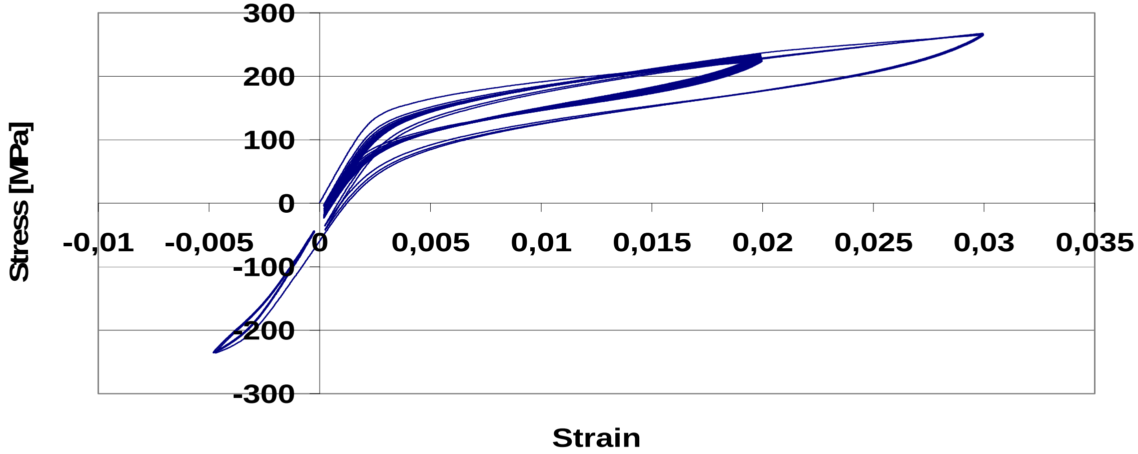


Test	Joint Connectivity	
D		**Φ6 Steel Bar**
E		**Φ6 Cu-based SMA Bar**

Cu-based SMA

Super-Elastic Behaviour

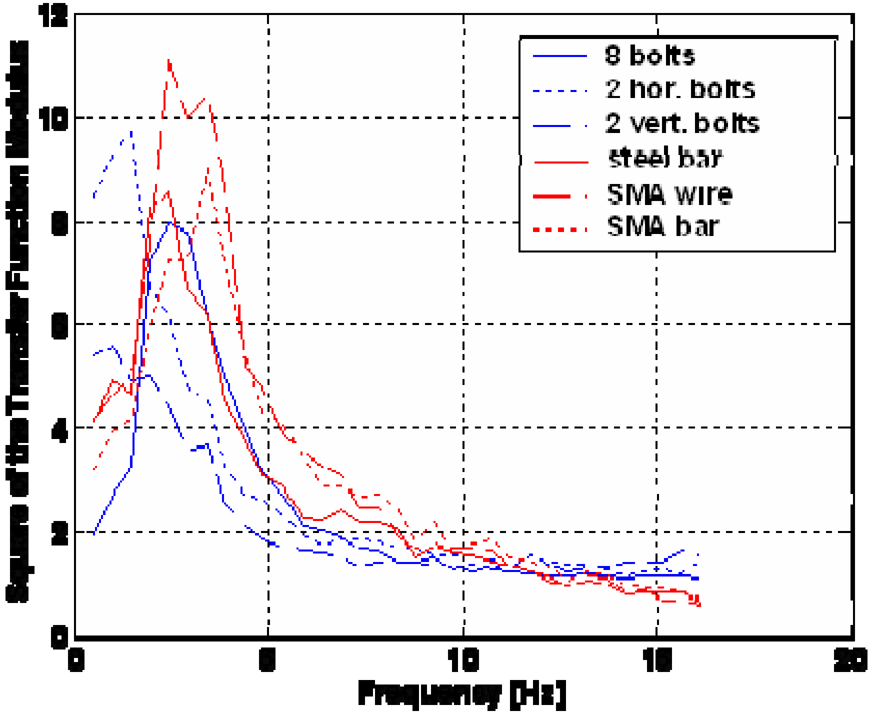
@ 30°C



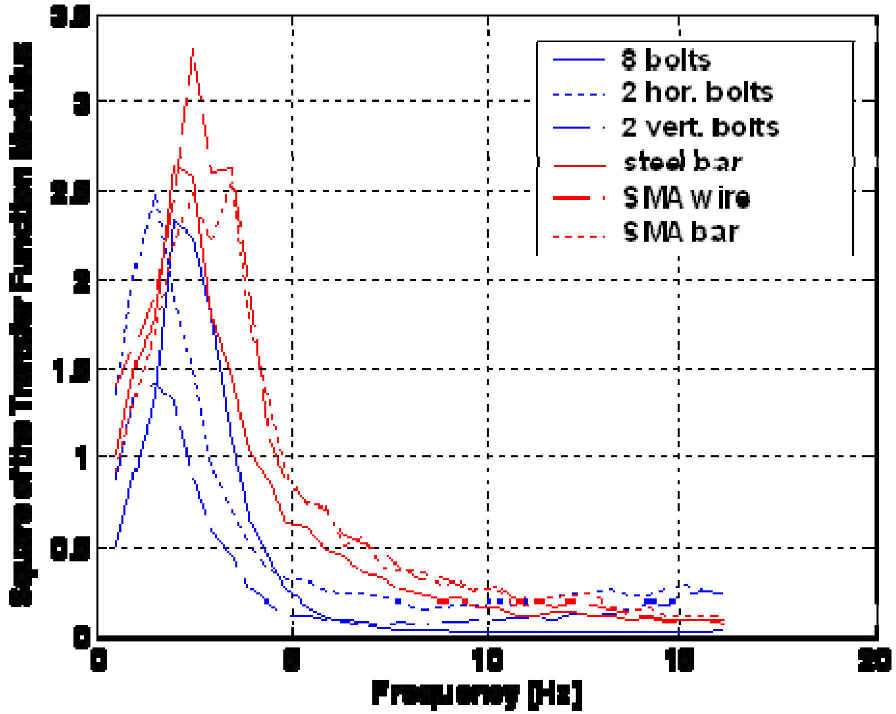
Testing Different Solutions for a Smart Joint Design

- Transfer Functions

Channel i = 0 (Sensor 1, X direction)



Channel i = 2 (Sensor 2, X direction)



Non-linear effects

By definition, the transfer function (or frequency response function) $Hj(f)$ is the complex function given by the ratio of the output Fourier tranform $Aj(f)$ and the one of the input $A7(f)$:

$$A_j(f) = H_j(f)\, A_7(f) \qquad j = 0, \ldots, 6 \tag{1}$$

Sjj denotes the two sided spectral density function (auto-spectrum),
$S7j$ is the two sided cross-spectrum

$$S_{jj}(f) = |H_j(f)|^2\, S_{77}(f) \tag{2}$$

$$S_{7j}(f) = H_j(f)\, S_{77}(f) \tag{3}$$

Let the single record be divided into *n* contiguous segments, with time step Δt and *N* points each.
For *m = 1, …, n*, one computes estimates, $Ajm(f)$, of the Fourier transforms, and performs averaging operations over the *n* records, in order to approximate the expected value that appears within an analytical context.

$$S_{jj}^{e}(f_h) = \frac{1}{nN\Delta t}\sum_{m=1}^{n}|A_{jm}(f_h)|^2 \quad h = 0,1,\ldots,N-1 \tag{4}$$

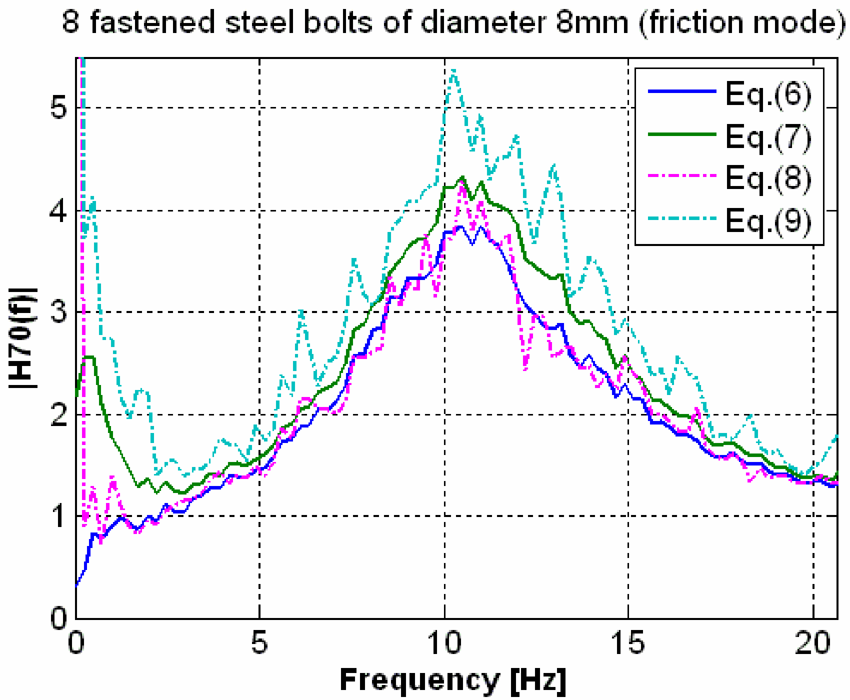
$$S_{7j}^{e}(f_h) = \frac{1}{nN\Delta t}\sum_{m=1}^{n}A_{7m}^{*}(f_h)A_{jm}(f_h) \quad h = 0,1,\ldots,N-1 \tag{5}$$

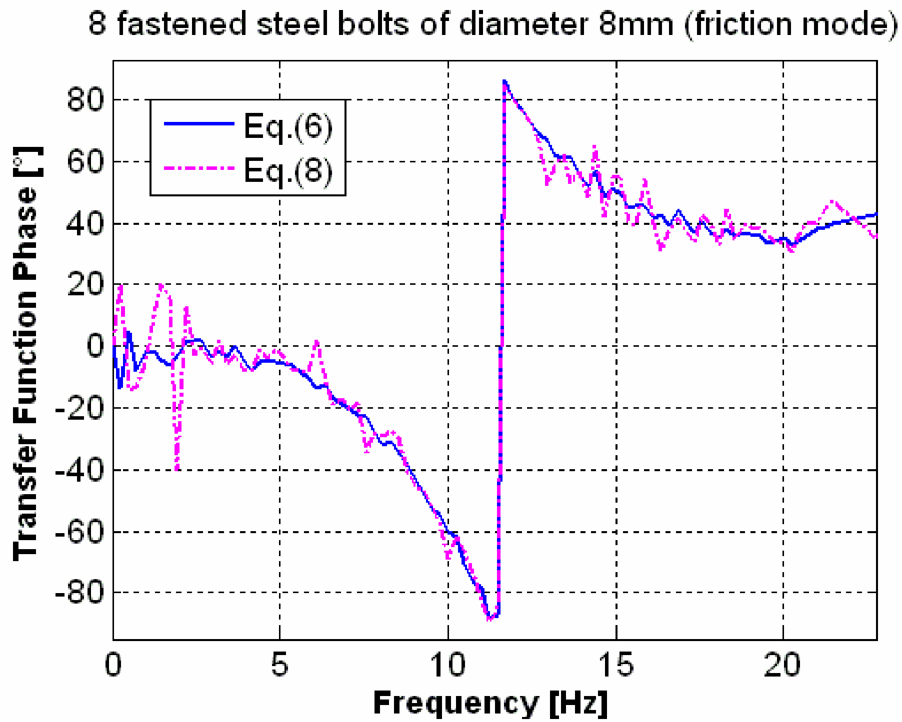
$$H_{7j}^{e}(f_h) = \frac{S_{7j}^{e}(f_h)}{S_{77}^{e}(f_h)} \tag{6}$$

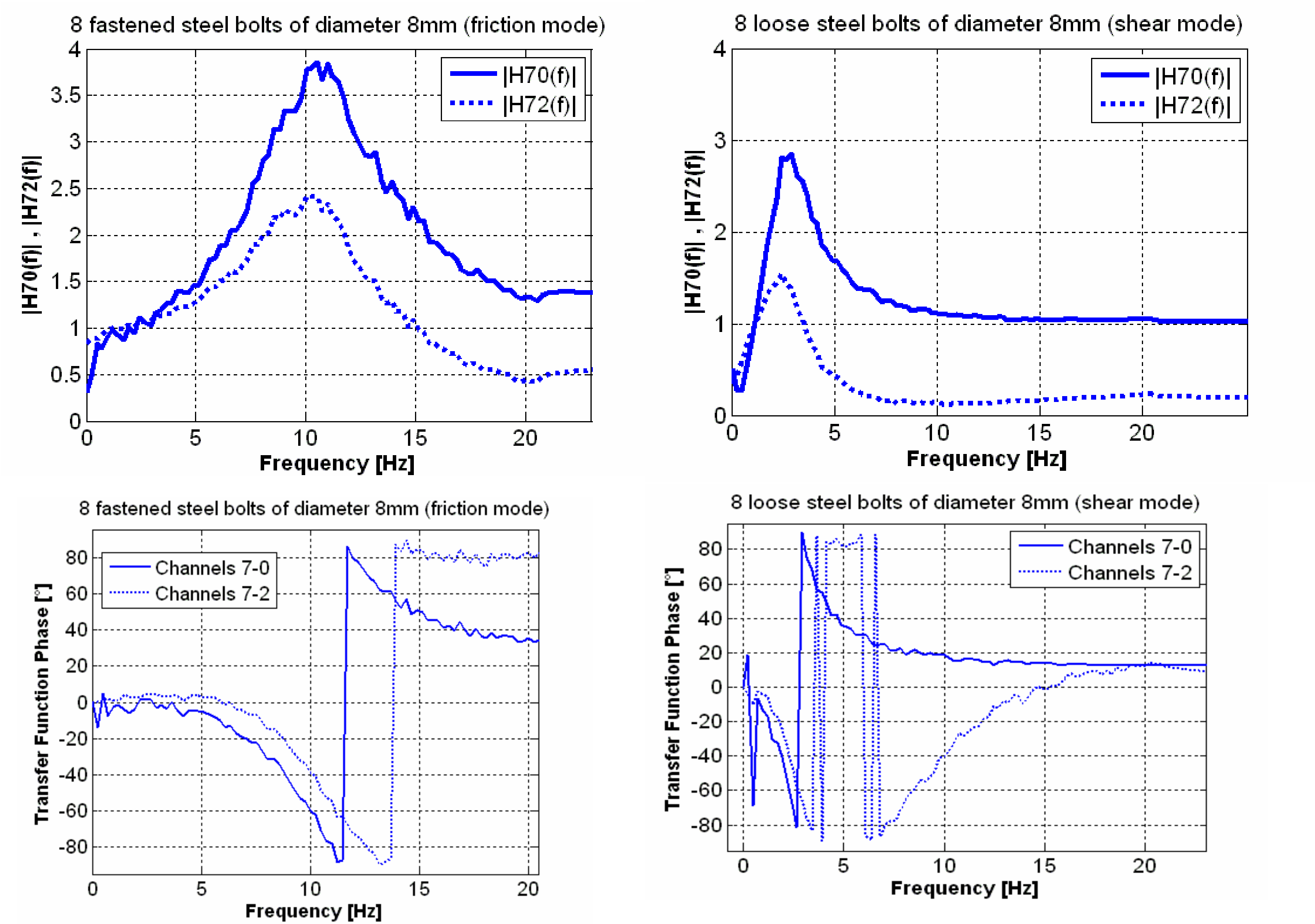
$$|H_{7j}^{e}(f_h)| = \sqrt{\frac{S_{jj}^{e}(f_h)}{S_{77}^{e}(f_h)}} \tag{7}$$

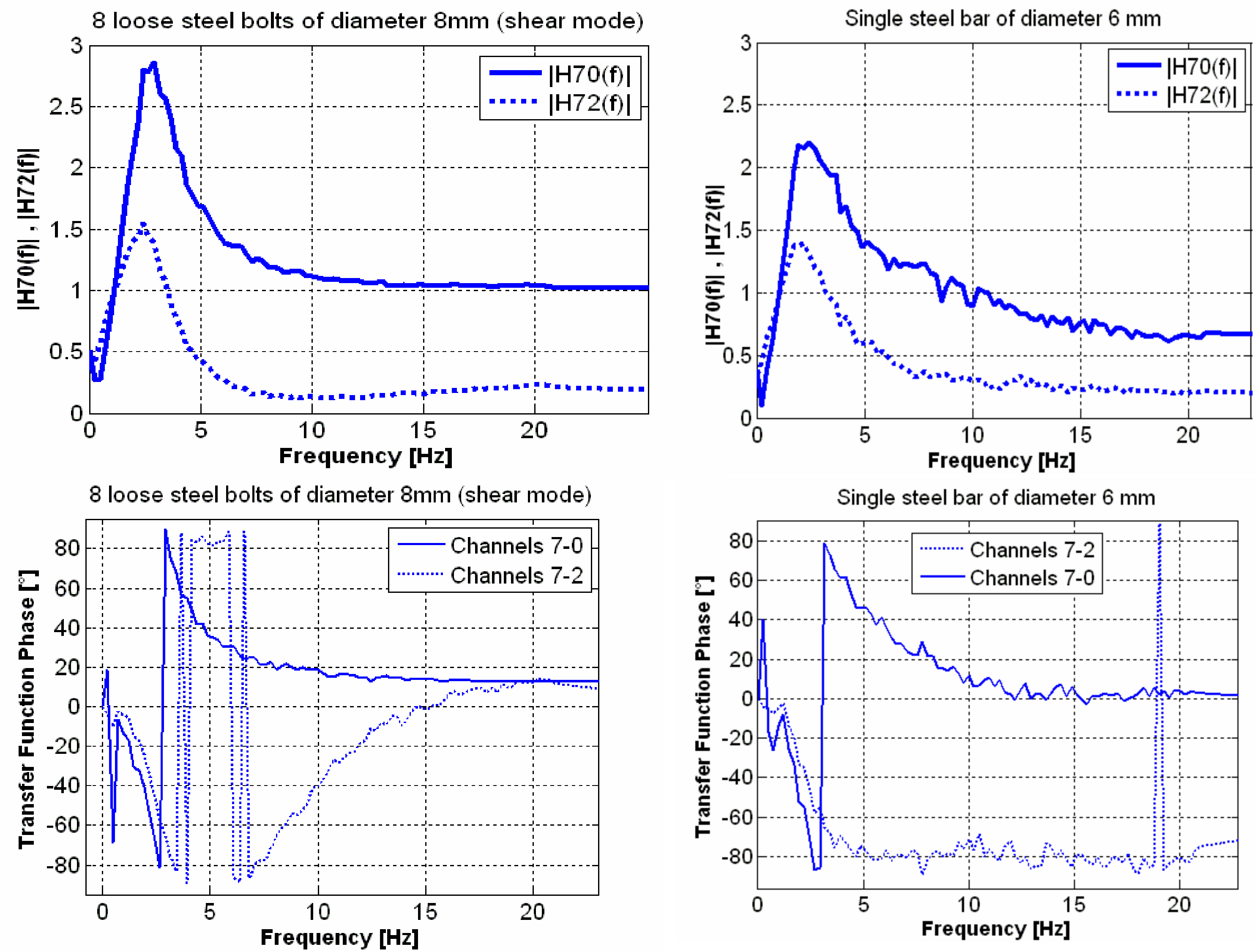
$$\overline{H}_{7j}^{e}(f_h) = \frac{1}{n}\sum_{m=1}^{n}\frac{A_{7m}^{*}(f_h)A_{jm}(f_h)}{A_{7m}^{*}(f_h)A_{7m}(f_h)} \quad h = 0,1,\ldots,N-1 \tag{8}$$

$$|\overline{\overline{H}}_{7j}^{e}(f_h)| = \frac{1}{n}\sum_{m=1}^{n}\frac{A_{jm}^{*}(f_h)A_{jm}(f_h)}{A_{7m}^{*}(f_h)A_{7m}(f_h)} \quad h = 0,1,\ldots,N-1 \tag{9}$$

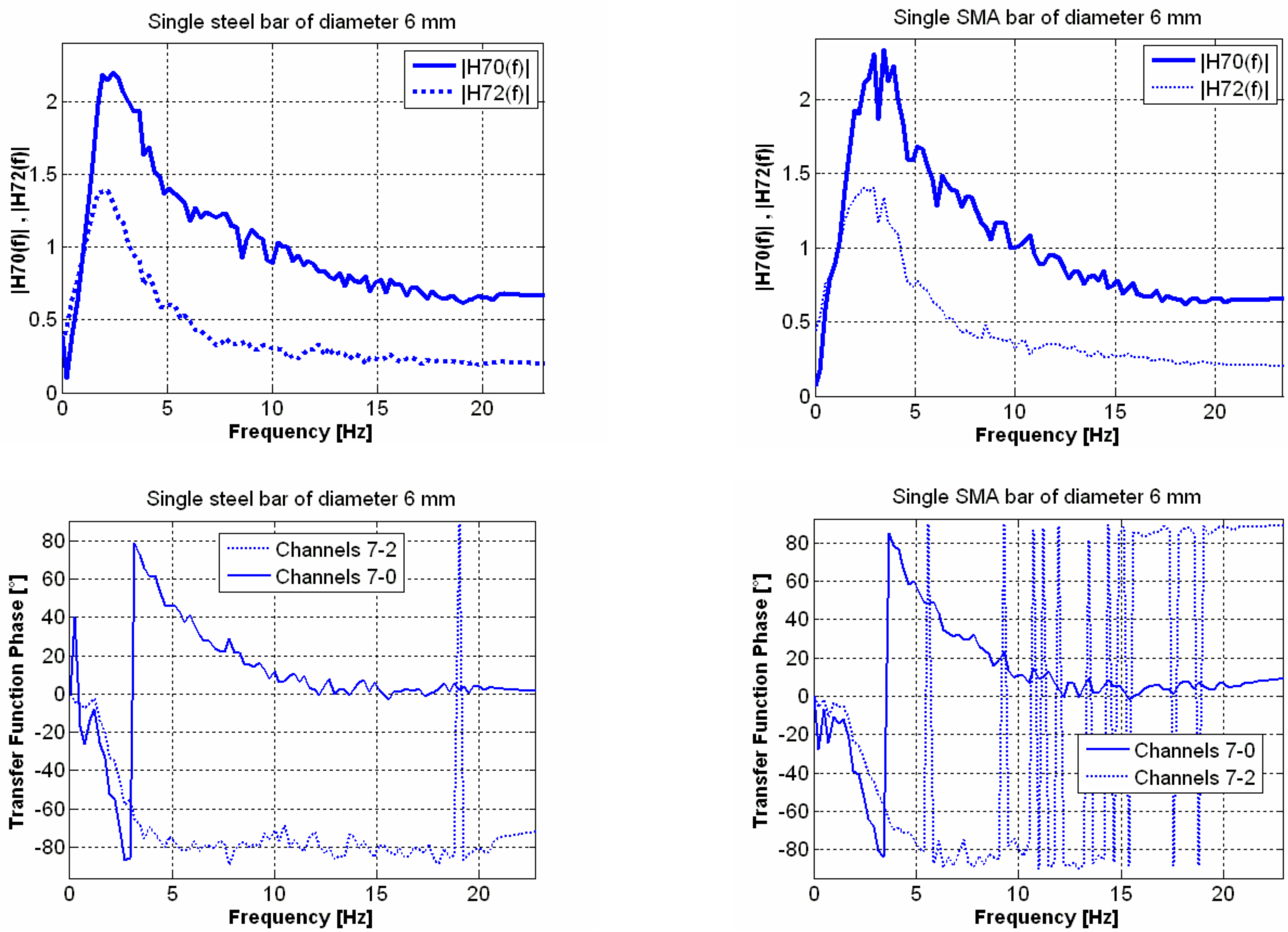

8 fastened steel bolts of diameter 8mm (friction mode)
|H70(f)|
Frequency [Hz]
Eq.(6)
Eq.(7)
Eq.(8)
Eq.(9)
0
1
2
3
4
5
0
5
10
15
20


8 fastened steel bolts of diameter 8mm (friction mode)
Transfer Function Phase [°]
Frequency [Hz]
Eq.(6)
Eq.(8)
80
60
40
20
0
-20
-40
-60
-80
0
5
10
15
20

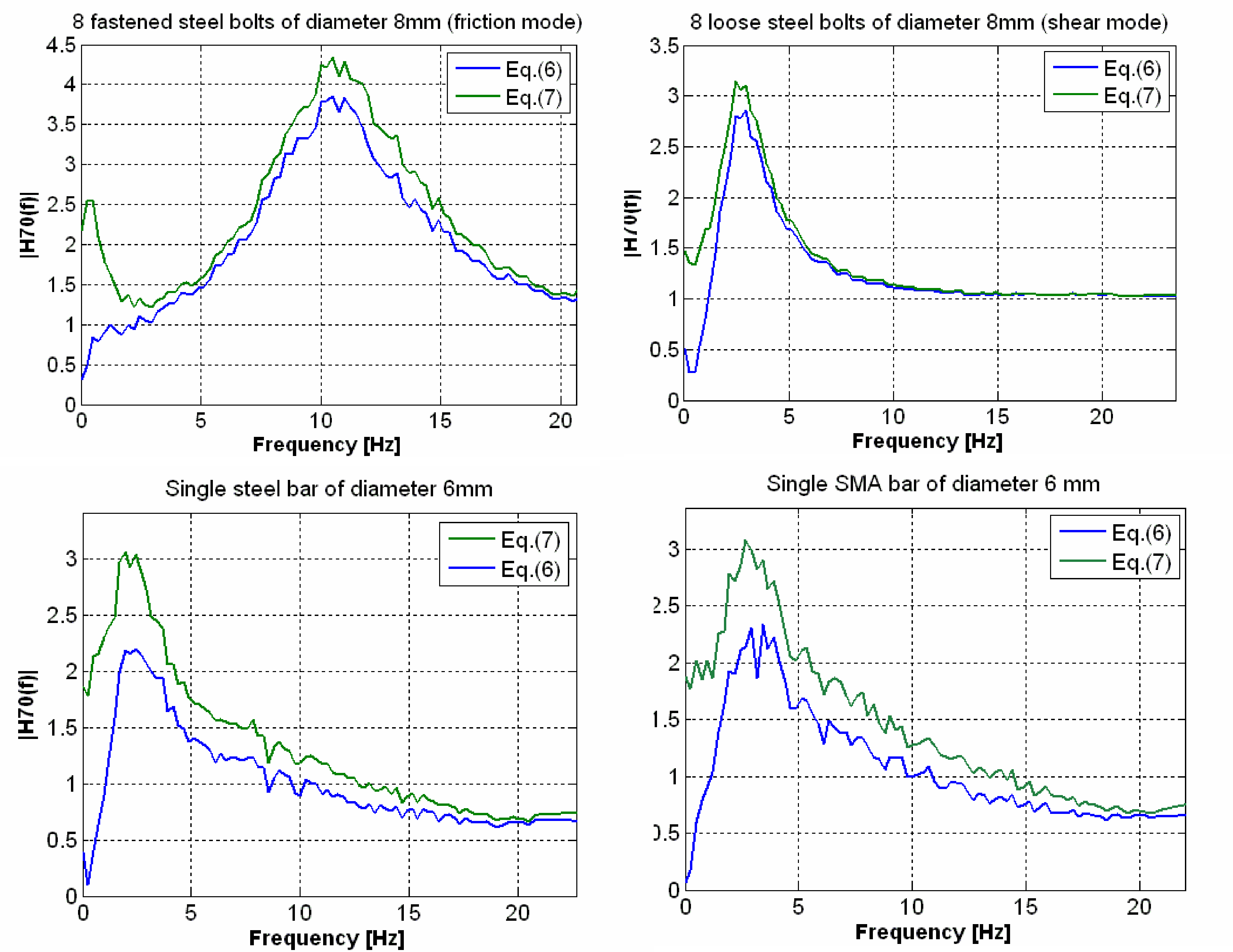

8 fastened steel bolts of diameter 8mm (friction mode)
|H70(f)|
|H72(f)|
|H70(f)| , |H72(f)|
Frequency [Hz]
8 loose steel bolts of diameter 8mm (shear mode)
|H70(f)|
|H72(f)|
|H70(f)| , |H72(f)|
Frequency [Hz]
8 fastened steel bolts of diameter 8mm (friction mode)
Channels 7-0
Channels 7-2
Transfer Function Phase [°]
Frequency [Hz]
8 loose steel bolts of diameter 8mm (shear mode)
Channels 7-0
Channels 7-2
Transfer Function Phase [°]
Frequency [Hz]



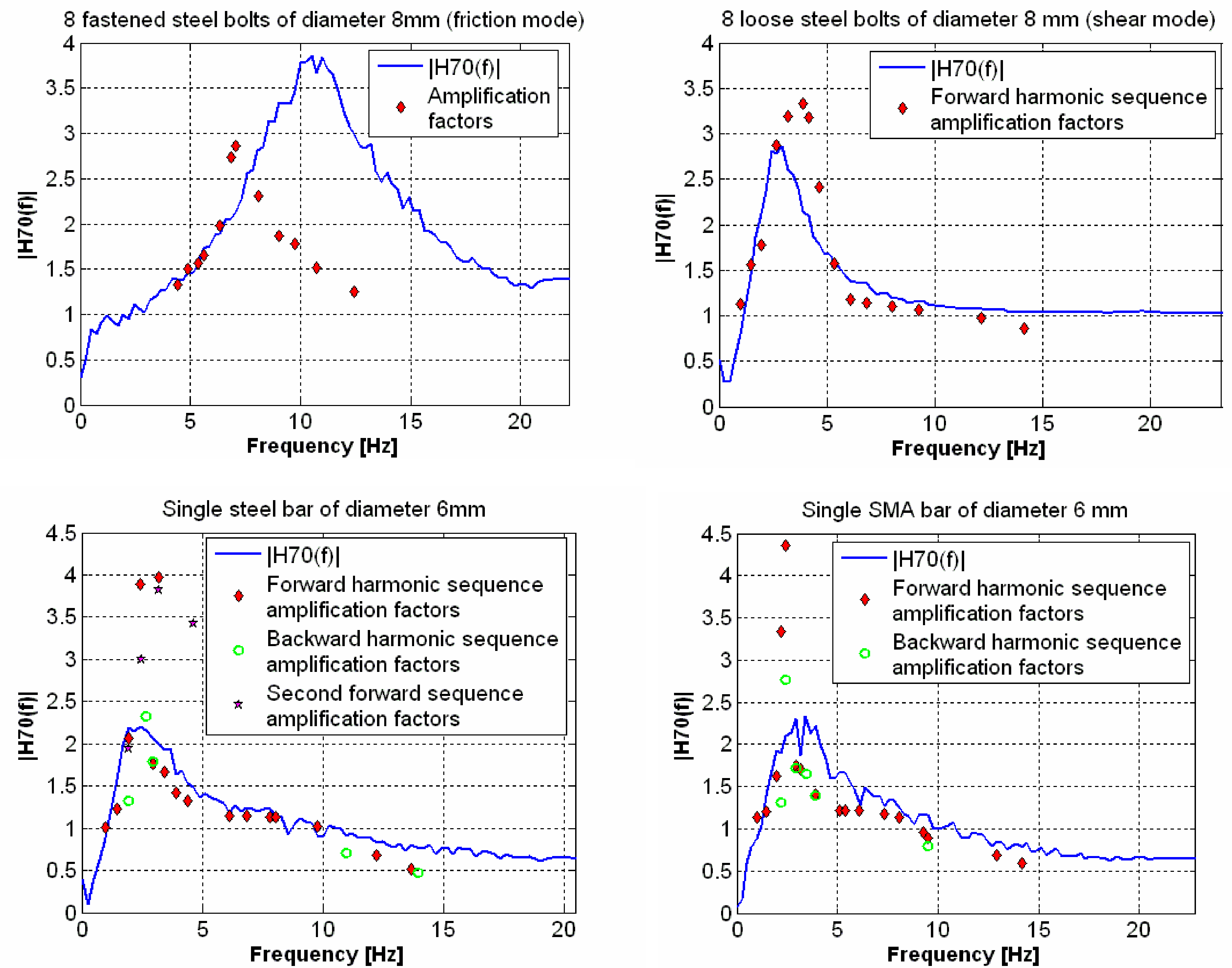
8 loose steel bolts of diameter 8mm (shear mode)
|H70(f)|
|H72(f)|
|H70(f)| , |H72(f)|
Frequency [Hz]
Single steel bar of diameter 6 mm
|H70(f)|
|H72(f)|
|H70(f)| , |H72(f)|
Frequency [Hz]
8 loose steel bolts of diameter 8mm (shear mode)
Channels 7-0
Channels 7-2
Transfer Function Phase [°]
Frequency [Hz]
Single steel bar of diameter 6 mm
Channels 7-2
Channels 7-0
Transfer Function Phase [°]
Frequency [Hz]



Single steel bar of diameter 6 mm
|H70(f)|
|H72(f)|
|H70(f)| , |H72(f)|
Frequency [Hz]
0
0.5
1
1.5
2
5
10
15
20
Single SMA bar of diameter 6 mm
|H70(f)|
|H72(f)|
|H70(f)| , |H72(f)|
Frequency [Hz]
Single steel bar of diameter 6 mm
Channels 7-2
Channels 7-0
Transfer Function Phase [°]
80
60
40
20
-20
-40
-60
-80
Frequency [Hz]
Single SMA bar of diameter 6 mm
Channels 7-0
Channels 7-2
Transfer Function Phase [°]
Frequency [Hz]



8 fastened steel bolts of diameter 8mm (friction mode)
|H70(f)|
Frequency [Hz]
Eq.(6)
Eq.(7)
8 loose steel bolts of diameter 8mm (shear mode)
Frequency [Hz]
Eq.(6)
Eq.(7)
Single steel bar of diameter 6mm
|H70(f)|
Frequency [Hz]
Eq.(7)
Eq.(6)
Single SMA bar of diameter 6 mm
Frequency [Hz]
Eq.(6)
Eq.(7)



8 fastened steel bolts of diameter 8mm (friction mode)
|H70(f)|
Amplification factors
Frequency [Hz]
8 loose steel bolts of diameter 8 mm (shear mode)
|H70(f)|
Forward harmonic sequence amplification factors
Frequency [Hz]
Single steel bar of diameter 6mm
|H70(f)|
Forward harmonic sequence amplification factors
Backward harmonic sequence amplification factors
Second forward sequence amplification factors
Frequency [Hz]
Single SMA bar of diameter 6 mm
|H70(f)|
Forward harmonic sequence amplification factors
Backward harmonic sequence amplification factors
Frequency [Hz]

Conclusions

- Shifting the bolts behaviour from friction mode to shear mode leads to very low resonant frequency values (i.e., very large periods), thus resulting into a base isolation effect: the system becomes insensitive to all excitations with energy contents in a frequency range higher than the resonant one.
- This effect can be achieved also by using a connectivity of smaller diameter than the designated hole. In this case, a slower decay of the transfer functions is observed.
- When a connectivity in SMA is adopted, an increase of the resonant frequency occurs relatively to the other solutions. This is due to its very low Young modulus with respect to steel. A significant comparison should be carried out between connections of the same global stiffness.
- The non linear aspects associated with the bolts release, and with the impact-contact sequence allowed by an enlargement of the designated hole have been considered and quantified.