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# DYNAMIC STIFFNESS AS AN ACOUSTIC SPECIFICATION PARAMETER FOR WALL TIES USED IN MASONRY CAVITY WALLS

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## 1. INTRODUCTION

Approved Document E[1] specifies that the leaves of cavity masonry separating walls (Wall Type 2) should be connected where necessary by butterfly ties. This generic type of wall tie is specified because of its ability to satisfy the structural requirements of BS5628[2] without compromising the dynamic isolation between the wall leaves which is necessary for sound insulation.

There are two main issues regarding the guidance given in Approved Document E for butterfly ties to be used in cavity masonry separating walls. Primarily it restricts flexibility for designers and contractors, although it does prevent unsuitable wall ties being used. The second issue is that the specification of a generic wall tie provides no incentive for the building materials industry to develop new wall ties and improve the dynamic properties of existing wall ties. A solution exists in the development and use of an acoustic specification parameter for wall ties which would benefit both regulators and industry.

This work has developed the measurement procedure for the dynamic stiffness of wall ties proposed by Craik and Wilson[3]. The aim was to find a robust measurement procedure and determine the dynamic stiffness of the generic butterfly tie for comparison with alternative wall ties.

## 2. THEORETICAL BACKGROUND

### 2.1 Mass-Spring-Mass theory

Consider only the transmission path between masonry cavity wall leaves via the wall ties. At low frequencies the cavity wall can be modelled[4] as a mass-spring-mass system where the wall leaves are represented by limp masses and the wall ties as springs. This mass-spring-mass system has a resonance frequency below which the wall leaves can be assumed to move together as a single limp mass. At the resonance frequency there is a peak in vibration transmission and the response of the receiving wall is dependant on the internal damping associated with the wall tie. Above the resonance frequency the vibration isolation of the two leaves increases with increasing frequency.

The mass-spring-mass resonance frequency, $f_{msm}$ (Hz) due to wall ties in a cavity wall is calculated from the dynamic stiffness of the wall tie, k ($Nm^{-1}$) in Equation 1.

**Equation 1**

$$f_{msm} = \frac{1}{2\pi}\sqrt{\frac{nk}{\left(\frac{\rho_{s1}\rho_{s2}}{\rho_{s1}+\rho_{s2}}\right)}}$$

where
n is the number of wall ties per square metre ($m^{-2}$)
k is the dynamic stiffness of a single wall tie ($Nm^{-1}$)
$\rho_s$ is the surface density of plate 1 or 2 ($kgm^{-2}$)

2.2 Wall tie bending wave modes
The mass-spring-mass model is no longer appropriate above the frequency at which the wall tie can support bending or longitudinal modes. Finite Element Methods are necessary to calculate fundamental resonance frequencies for the majority of wall ties because they do not have simple shapes. However, a satisfactory estimate can be found by treating the wall tie as a straight homogenous beam clamped at both ends[4]. The fundamental bending and longitudinal mode frequencies for typical wall tie materials and dimensions for cavity widths of 50mm will generally tend to be above 5kHz. Transmission due to modes on common wall ties is most likely to occur above the building acoustics frequency range (100Hz-5kHz).

2.3 Non-linear springs
For linear mechanical systems, the mass-spring-mass resonance curve is symmetrical about the resonance frequency and is independent of the applied force or the strain applied to the material. For non-linear systems[4,5], the resonance curves are no longer symmetrical and have decreasing or increasing values for the resonance frequency with increasing excitation level. A system with velocity dependant damping has non-linear damping. This damping can increase or decrease with increasing excitation level.

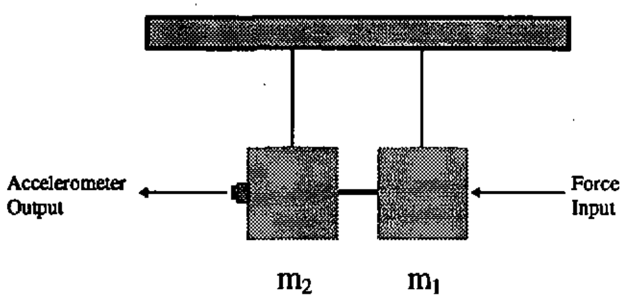
3. RESONANCE FREQUENCY MEASUREMENT

3.1 Experimental test rig
Craik and Wilson[3] have proposed a method for the determination of the dynamic stiffness of wall ties from the axial mass-spring-mass resonance frequency. Both ends of the wall tie are cast into concrete cubes (100mm side length) and the cubes and wall tie are supported by wire. The test rig for the measurement of the resonance frequency is shown in Figure 1.

3.2 Concrete cube specification

The concrete mix is required to rigidly hold the wall tie to ensure that only the dynamic properties of the wall tie are measured. It is noted that dynamic stiffness data from measurements using concrete cubes may overestimate the actual mass-spring-mass resonance frequency for walls. This is due to the difference in the fixing of wall ties in mortar and concrete. For comparative purposes it is necessary to standardise upon a single material so that alternative ties can be compared to butterfly ties. All measurements in this report used concrete cubes. The materials, quantities and the mixing process are specified for the concrete mix to ensure reproducibility.

**Figure 1: Experimental test rig for resonance frequency measurement**




3.3 Product specimens

The dynamic stiffness was determined for three generic types of steel wall tie (Butterfly, Double-triangle and Vertical-twist). The tie spacing (cavity width) used in the measurements was 50mm for all samples. This is the minimum cavity width described in Approved Document E masonry cavity wall constructions and hence gives the largest values of dynamic stiffness.

The butterfly ties conformed to BS1243[6] and represented the two permissible wire thickness values. Six butterfly ties of each of the two wire thicknesses were tested. The specifications for the two types of butterfly tie were as follows:

- Stainless steel wire (2.6mm diameter) of minimum tensile strength $460Nmm^{-2}$.
- Galvanised low carbon steel wire (3.15mm diameter) of minimum tensile strength $370Nmm^{-2}$. (Galvanised according to BS1243 : 1978 (Amended))

3.4 Measurement of the axial mass-spring-mass resonance frequency

The measurement requires a force transducer to measure the force input to the source block $m_1$ and an accelerometer to measure the output acceleration on the receive block $m_2$. Calibration of the force transducer is carried out according to BS 6897[7]. The applied force input and the acceleration output are both measured at the centre point on the cube surface. The acceleration and force signals were taken to a dual channel FFT analyser for calculation of autospectra and Frequency Response Functions which were used to determine phase relationships between the two signals. The resonance frequency can be found by finding the peak level of the acceleration autospectrum or by finding the frequency at which the phase of the Frequency Response Function was closest to 90 degrees.

If the peak level in the autospectrum is used to find the resonant frequency it should be noted that there are different resonance frequencies for the displacement, velocity and acceleration autospectrum with any damped mass-spring system. For many real systems the difference is negligible. For accuracy, the velocity autospectrum should be used to determine the resonance frequency from the resonance peak. However, the Q factor ('sharpness') of the peak in the velocity autospectrum is dependent upon the internal damping of the wall tie whereas the 90 degree phase difference is unaffected by the damping. The most accurate method to determine the resonant frequency therefore uses the phase difference rather than the velocity autospectrum peak to determine the undamped resonance frequency. (See Figure 2 for an example measurement of the resonance peak and the phase difference) All measured data used the 90 degree phase difference to determine the resonance frequency.

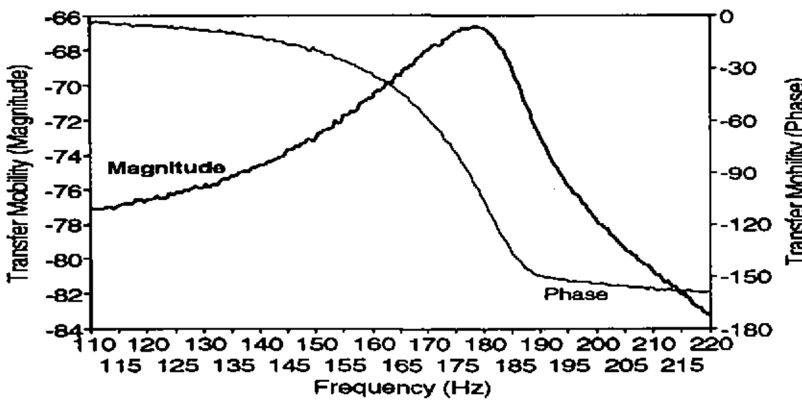



**Figure 2: Frequency Response Function in terms of the magnitude and phase for impulse excitation of a wall tie at resonance.**

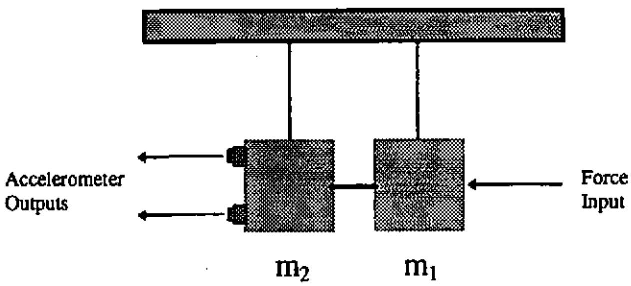
3.5 Identifying the axial mass-spring-mass resonance frequency

In order to measure the axial mass-spring-mass resonance frequency, it must be distinguishable from any other resonant modes of the system such as twisting and oblique modes, bending and longitudinal modes of the tie or resonant modes of the concrete cube. All these resonant modes must

occur at frequencies other than the axial mass-spring-mass resonance frequency in order for measurements to be used to determine the dynamic stiffness.
From Wilson[8], the axial mode of vibration can be identified using two accelerometers on cube $m_2$. This secondary measurement set-up is shown in Figure 3. The axial mode can be identified by the peak in the accelerometer autospectrum from the primary measurement set-up that corresponds to a zero degree phase difference between the two accelerometer signals in the secondary measurement set-up. The butterfly tie is different from many other wall ties because there is no continuous connection along its longest axis that is perpendicular to the block surface. It is therefore necessary to distinguish the axial mode from the oblique mode which is often excited simultaneously due to the angle of the continuous connection.

For a concrete cube of side length 100mm, the lowest resonance frequency of the cube is expected to occur above the frequency range for typical wall tie mass-spring-mass resonances.

**Figure 3: Experimental test rig for identifying the axial mass-spring-mass resonance frequency**




3.6 Excitation signal

BS EN 29052-1[9] concerns the determination of dynamic stiffness for fibrous materials and acknowledges that white noise and impulse excitation can give different values for the resonance frequency in comparison to sinusoidal signals. BS EN 29052-1 states that the resonance frequency can be determined using either sinusoidal, white noise or pulse signals and that all these methods are equivalent but in case of dispute, the sinusoidal signal shall be the reference method. It would therefore seem prudent to suggest that sinusoidal signals should be used for all resonance frequency measurements. White noise and impulse excitation can be used to determine an estimate for the resonance frequency. This estimate can then be used as the initial frequency at which sinusoidal excitation is applied.

Sinusoidal excitation requires the force transducer to be rigidly attached to source block $m_1$. This was achieved by bonding a nut to the concrete cube using adhesive so that the force transducer could be threaded into the nut.

3.7 Non-linearity and the mass-spring-mass resonance frequency

If a wall tie acts as a non-linear spring, the mass-spring-mass resonance frequency will be dependant on the excitation force. The high crest factor associated with impulse excitation can cause non-linear behaviour. The non-linear spring behaviour of wall ties was demonstrated using different levels of impulse excitation with a force hammer.

The impulse excitation results for four wall ties are shown in Figure 4 to Figure 7. They are shown using the transfer mobility magnitude for different input force values in terms of the Energy Spectral Density (ESD in $N^2sHz^{-1}$). These results show that the resonance frequency is significantly affected by the excitation level and that wall ties can act as non-linear springs. The results also indicate that wall ties can have non-linear damping where the damping increases with increasing excitation level. This is indicated by the decrease in the peak level of the transfer mobility magnitude and the increase in the 3dB bandwidth.

3.8 Extrapolated resonance frequency

Because of the non-linear behaviour, determination of dynamic stiffness according to BS EN 29052-1 for resilient materials used in floating floors requires extrapolation to find the extrapolated resonant frequency $f_r$ in Hz at zero force amplitude. The zero force situation cannot occur in reality but is a pragmatic solution to the non-linearity problem which allows the comparison of dynamic stiffness for different wall ties. A suitable range of force values for extrapolation has been derived from wall tie measurement data with examples shown graphically in Figure 8 to Figure 10. The graphs show the variation of the resonance frequency with RMS force input from sinusoidal excitation. Two force ranges have been chosen for the determination of the extrapolated resonant frequency, 0.01N - 0.1N and 0.1N - 0.8N.

It is difficult to identify a single force range that is representative of the force exerted on a wall tie in a cavity wall construction due to different wall densities, variation in wall tie fixing and wall tie shape. The choice of force range can be pragmatically determined by a range that introduces minimal measurement error and does not underestimate the extrapolated resonance frequency. It should be noted that the determination of wall tie dynamic stiffness is primarily required for the comparison of different types of wall ties.

The force range 0.01N - 0.1N with sinusoidal excitation has been chosen as the most suitable force range based on the following points:

- In the majority of measurements, the force range 0.01N - 0.1N gives a higher value of $f_r$ than the force range 0.1N - 0.8N. (For regulatory purposes the dynamic stiffness should not be underestimated.)
- Force range 0.01N - 0.1N consistently shows a decrease in resonance frequency with increasing force for all measured wall ties. For the force range 0.1N - 0.8N there were three butterfly ties which showed an increase in resonance frequency with increasing force.
- The maximum difference between $f_r$ from the twelve butterfly tie measurements with the two different force ranges was 3.2Hz. This would give a difference in dynamic stiffness of

0.06MNm$^{-1}$. For wall ties with higher values of dynamic stiffness, the difference between the two force ranges becomes significant when the dynamic stiffness is to be quoted to one decimal place in MNm$^{-1}$. Only one force range should be used to ensure consistency.

## 4. DETERMINATION OF DYNAMIC STIFFNESS

The dynamic stiffness, k (Nm$^{-1}$) is defined using Equation 2.

**Equation 2**

$$k = \frac{(2\pi f_r)^2}{\left(\frac{m_1+m_2}{m_1 m_2}\right)}$$

where
$f_r$ is the extrapolated resonant frequency (Hz)
$m_1$ is cube mass 1 (kg)
$m_2$ is cube mass 2 (kg)

The casting process for the concrete cubes prevents individual measurement of $m_1$ and $m_2$ without cutting the wall tie flush to the surface of each cube. However, the mass variation between cubes is minimised through accurate specification of the concrete mix quantities. An average mass value for a single cube $m_{average}$ (kg) can be found using Equation 3.

**Equation 3**

$$m_{average} = \frac{(m_1+m_2+m_{tie})-m_{tie}}{2}$$

where
$m_{tie}$ is the mass of the wall tie (kg)

The dynamic stiffness k (Nm$^{-1}$) can be found using Equation 4.

**Equation 4**

$$k = 2\pi^2 f_r^2 m_{average}$$

### 4.1 Accuracy

The accuracy of the dynamic stiffness value is determined by the extrapolated resonance frequency $f_r$ and the average cube mass $m_{average}$. Errors due to the determination of $f_r$ are not significant when $f_r$ is approximately 200Hz because FFT analysers can provide frequency line resolution less than 1Hz with and without FFT zoom. The cubes and wall tie do not need to be measured to an accuracy greater than ±0.002kg. It is also noted that the calculation of an average value for the cube mass $m_{average}$ will not cause significant errors assuming that the concrete mix is uniform and that both cubes are similarly consolidated.

Because of the variation between wall tie samples and wall tie fixing in the concrete cubes it is necessary to measure a number of samples and determine the standard deviation for each type of wall tie.

## 5. RESULTS

The statistical dynamic stiffness data for butterfly ties and single values for a double-triangle tie and vertical-twist tie measured using sinusoidal excitation with the extrapolation force range 0.01N - 0.1N are shown in Table 1. The stainless steel and galvanised butterfly ties have the same mean value and standard deviation hence there is no significant difference between the two types of butterfly tie described in BS1243. Examples of dynamic stiffness measurement data for wall ties with 50mm spacing, sinusoidal excitation and the extrapolation force range 0.01N - 0.1N are shown in Figure 8 to Figure 10. The average value for the cube mass $m_{average}$ was 2.28kg.

**Table 1: Dynamic stiffness data for wall ties (50mm spacing)**

| Type of wall tie | Dynamic Stiffness Mean Value ($MNm^{-1}$) | Dynamic Stiffness Standard Deviation ($MNm^{-1}$) | Number of samples |
|---|---|---|---|
| Butterfly (2.6mm Stainless steel) | 1.7 | 0.1 | 6 |
| Butterfly (3.15mm Galvanised steel) | 1.7 | 0.1 | 6 |
| Double-triangle | 16.1 | - | 1 |
| Vertical-twist | 94.0 | - | 1 |

## 6. IMPLEMENTATION

A suitable specification for alternative wall ties to the butterfly tie should be based on butterfly tie dynamic stiffness data with reference to vibration transmission between the cavity wall leaves. Wall tie dynamic stiffness as an acoustic specification parameter for regulatory purposes is more robust than the comparison of wall ties using sound insulation measurements of masonry cavity walls in a transmission suite. This is due to variations in the sound insulation for nominally identical cavity walls built in the laboratory and the unknown strength of transmission between the two wall leaves via the sound field in the cavity. The dynamic stiffness parameter allows a wall tie of equivalent dynamic stiffness to the butterfly tie to be identified without involving other variables for the masonry cavity wall construction such as cavity damping and structural coupling at the wall boundaries. It also allows independent assessment of the wall tie without needing to test the different masonry cavity wall constructions which have different material density and Young's Modulus. Calculations using dynamic stiffness can therefore be used to justify the value of dynamic stiffness for an alternative wall tie that can be deemed equivalent to the butterfly tie for sound insulation purposes.

Wall ties should provide increasing vibration isolation of the wall leaves with increasing frequency above the mass-spring-mass resonance frequency. However, at the mass-spring-mass resonance frequency, the isolation can be adversely affected. Calculated values for the mass-spring-mass resonance frequency of Approved Document E wall type 2 (cavity masonry) constructions A, B and C are typically below 50Hz.

From Craik and Wilson[3] the Coupling Loss Factor $\eta_{12}$ (CLF) between wall leaves 1 and 2 due to connection by wall ties of known dynamic stiffness can be calculated using Equation 5.

**Equation 5**

$$\eta_{12} = \frac{nY_2}{\omega\rho_{S1}\left[\left(Y_1 + Y_2\right)^2 + \left(\frac{\omega}{k}\right)^2\right]}$$

where
n is the number of wall ties per square metre ($m^{-2}$)
$Y_1$ is the mobility of plate 1
$Y_2$ is the mobility of plate 2
$\rho_{S1}$ is the surface density of plate 1 ($kgm^{-2}$)
$\omega$ is the angular frequency (radian $s^{-1}$)

An increase in the mean value of butterfly tie dynamic stiffness ($1.7MNm^{-1}$) by $0.1MNm^{-1}$ increases the CLF for Approved Document E wall type 2 (cavity masonry) constructions A, B and C by 0.5dB. This increase of $0.1MNm^{-1}$ corresponds to one standard deviation and also corresponds to the 95% confidence interval when calculated to one decimal place using the students t distribution for the 12 butterfly tie samples. When all sound transmission between two rooms takes place across the separating masonry cavity wall via the wall ties, an increase in the CLF of 0.5dB corresponds to a decrease in the sound insulation of approximately 0.5dB. Transmission involving only the wall ties is justifiable because the aim is to identify alternative wall ties that can be deemed equivalent to the butterfly tie.

The specification of a dynamic stiffness value for alternative wall ties based on butterfly tie dynamic stiffness requires a robust yet concise and practical definition. If the mean butterfly tie dynamic stiffness value is used, the standard deviation of the results must be taken into account. This is justified by the decrease in the sound insulation of 0.5dB that has been calculated when the butterfly tie mean dynamic stiffness plus one standard deviation was used. It is reasonable to assume that alternative wall ties will not show significantly greater variation than the butterfly tie and therefore a sample of six alternative wall ties could be tested. This approach enables the requirement for alternative wall ties to be specified without reference to statistical data other than the mean value. If the measurement report is required to state the six individual values along with the mean value, any significant differences can be identified.

A suitable alternative wall tie to the butterfly tie can be defined as one with a mean dynamic stiffness value from six samples that is less than or equal to $1.7MNm^{-1}$. Assumptions made in this definition are listed below:

- The internal loss factor (internal damping) of a wall tie affects the amount of vibration transmission at the mass-spring-mass resonance frequency. Two main reasons against the specification of an amount of damping greater than or equal to the damping for the butterfly tie are:

  (1) Measurement of the internal loss factor is liable to error when springs have non-linear behaviour. If the springs are softening or hardening spring types, the 3dB bandwidth is not equally spaced on either side of the resonance frequency. A significant error also occurs when the damping is velocity dependent (ie non-linear damping). The damping is also dependant on the material into which the tie is fixed.

  (2) The mass-spring-mass resonance frequency for cavity masonry walls is often designed to occur below the building acoustics frequency range of measurement hence the internal damping is not strictly relevant for regulatory purposes.

- Concrete has been used instead of mortar so that the dynamic stiffness is related as closely as possible to the property of the wall tie rather than the fixing of the tie in the mortar between the blockwork in the field situation. (NB Dynamic stiffness data from measurements using concrete cubes may therefore overestimate the actual mass-spring-mass resonance frequency for cavity masonry walls.)

- Generic butterfly ties are limited by BS5628 to cavity widths between 50mm and 75mm with a minimum masonry leaf thickness of 90mm. It is suggested in this report that dynamic stiffness is only determined for wall ties with 50mm separation. This will minimise the measurement costs. If an alternative wall tie is deemed to be of equivalent dynamic stiffness to a generic butterfly tie using 50mm separation then the following statement regarding the sound insulation is applicable.

  > 'The sound insulation of a masonry cavity wall with a 75mm cavity can be no lower than that of the same masonry cavity wall with a 50mm cavity when the same wall ties are used in both walls and all transmission of vibration between the two wall leaves takes place via the wall ties.'

  For compatibility with the current Approved Document E, it is sufficient that transmission is only considered via the wall ties.

## 7. CONCLUSIONS

- The test method proposed by Craik and Wilson[3] is suitable when sinusoidal excitation is used. The resonance frequency for the determination of the dynamic stiffness value must be found by extrapolation to find the resonance frequency at 0N force input. This is necessary because impulse excitation can give rise to decreasing or increasing resonance frequency values with increasing excitation level due to the non-linear spring behaviour of wall ties.

- A suitable alternative wall tie to the butterfly tie can be defined as one with a mean dynamic stiffness value from six samples that is less than or equal to $1.7 MNm^{-1}$.

- Mass-spring theory can be used to predict sound transmission across wall ties using measured values of dynamic stiffness. The theory is sufficiently simple and concise to facilitate the introduction of dynamic stiffness as a specification parameter.

- It would be of benefit to both regulators and industry to formalise a method for the determination of dynamic stiffness for wall ties in a British or European standard.

## ACKNOWLEDGEMENT

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**Impulse response for different ESD values. (ESD units: $N^2sHz^{-1}$)**

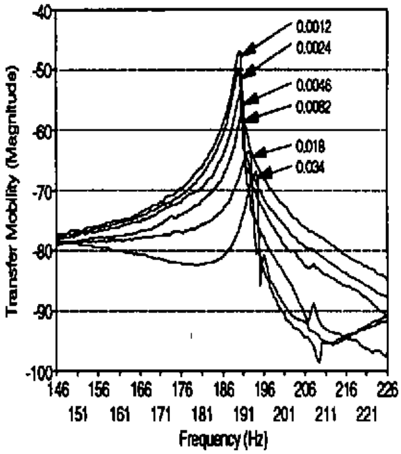


**Figure 4: Butterfly Tie (Stainless Steel)**

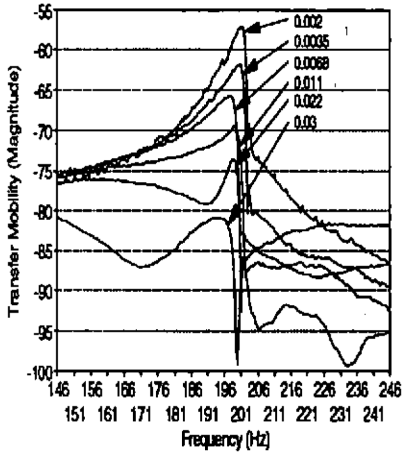


**Figure 5: Butterfly Tie (Galvanised steel)**

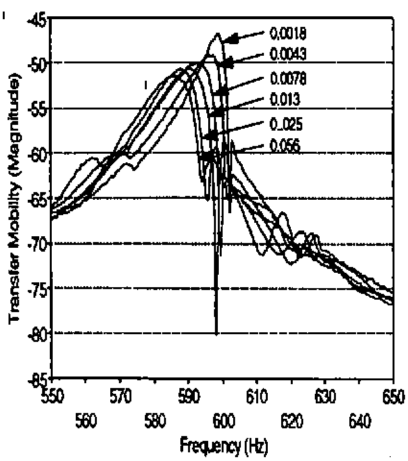


**Figure 6: Double-triangle Tie**

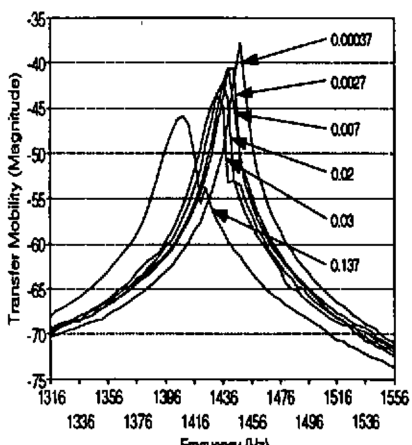


**Figure 7: Vertical-twist Tie**

**Sinusoidal excitation: Extrapolated resonance frequency**

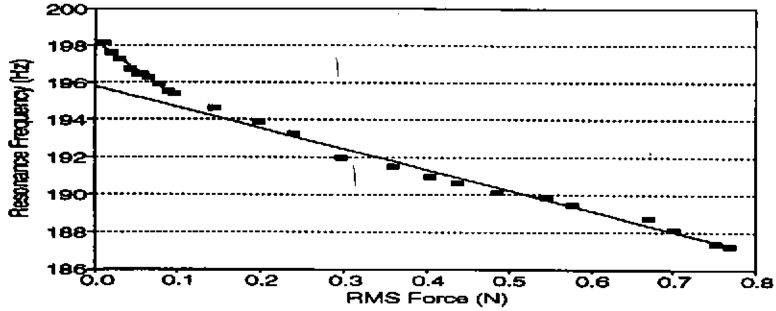


**Figure 8: Butterfly Tie (Galvanised steel)**

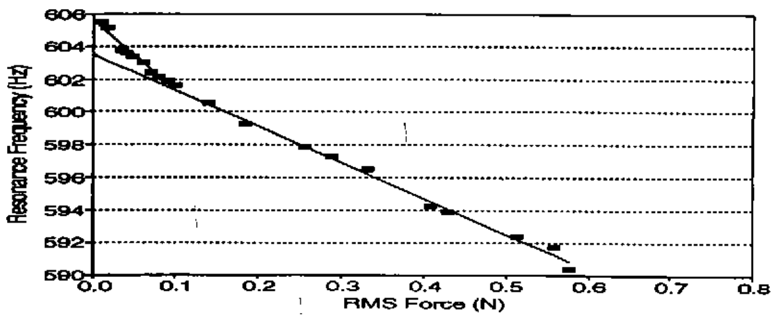


**Figure 9: Double-triangle Tie**

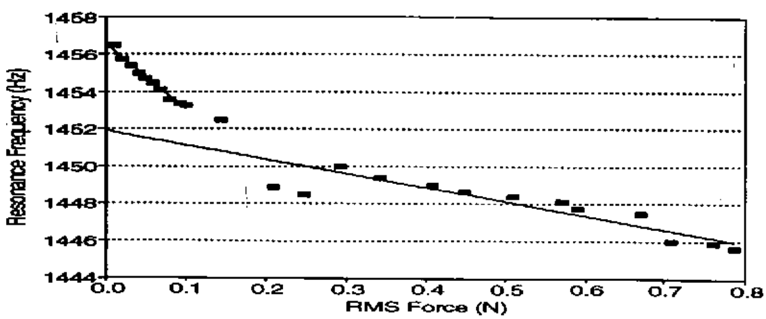


**Figure 10: Twist Tie**