Chapter 16
Vibration-Based Non-Destructive Techniques for a 3-Level Characterization of Damages in Cables

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Abstract For the characterization of damages of cables, tests have been performed on a safe seven-wire strand which is equipped with eight contactless laser sensors recording the transverse displacements. After this first phase, the same experiments are done on the same cable but with one broken wire, out of the seven. The data (dynamic parameters) from a safe and damaged cable are then compared. For a full damage characterization, the main aim is being able to detect (level 1), locate (level 2), quantify the damage severity (level 3) and predict remaining service lifetime (level 4) of the structure. However vibration-based methods are well known in the literature to provide levels 1 and 2 (detection and location) of damage identification but it seems challenging to go further using only these methods. In this paper, using modal analysis in the frequency domain, detection and location of damage are made. Then a second and a third damages are made in the cable gradually in order to increase the damage severity. Based on the natural frequencies that are less affected by experimental errors and simple to determine, a parameter to estimate the damage severity is provided at the end. Consequently, that allows attaining the level 3 in damage characterization.

Keywords Cables · Damages severity · Modal analysis · Natural frequencies · C_i parameter

16.1 Introduction

Cables are of the critical structural parts of cable-stayed bridges and suspension bridges. These cables are, through their structural life, submitted to different types of solicitations: mechanical loads, thermal loads and chemical attacks. Such actions generate two main pathologies that are corrosion and another one known as fretting-fatigue [1, 2]. Fretting-fatigue is a combination of fatigue solicitations and friction between wires constituting the cable [3]. These pathologies, when not detected early enough and cured, can lead to severe damages not excluding collapse. Thereby, it demonstrates the necessity of monitoring the health of such structures for users' safety. Hence, many non-destructive techniques (NDT) have been developed all along the years to come over these issues. Of these NDT, we have the eddy current inspection, magnetic fields-based inspection, radiographic testing, acoustic emission (AE), vibration-based methods, etc. A review of some of these NDT is given in [4]. In this current work, vibration-based techniques are used in order to evaluate the structural health of cables. In other words, the objectives are, at first to give to practitioners a mean to detect and evaluate damage (wire breaks) severity in cables and then to locate the damage so it can be repaired if necessary.

Therefore, for this work, tests have been performed on a safe seven-wire strand equipped with eight contactless laser sensors recording the transverse displacements where the excitations are made by hammer impacts. After this first phase, the same experiments are carried out on the same cable but with one broken wire, out of the seven. This will allow comparing data (dynamic parameters) from a safe and damaged cable. For a full damage characterization, four levels are defined: the detection, the location, the quantification of the damage severity and the prediction of the remaining service lifetime of the structure [5]. In [6], authors emphasize that vibration-based methods provide levels 1 and 2 (detection and location) but not further; this is also noticed by Le Petit [7]. In this paper, using modal analysis in the frequency domain, detection and location of damage in cable are made. Then a second and a third damages are introduced in the cable gradually in order to increase the damage severity. Based on the natural frequencies that are less affected by experimental errors and simple to determine,

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a parameter enabling to estimate the damage severity is provided at the end. Consequently, that allows attaining the level 3 in damage characterization that is the damage severity quantification.

16.2 Background

For the analysis of the vibration data, we have used methods based on experimental modal analysis (EMA) since the impact hammer used gives the excitation force. The modal analysis is the extraction of modal parameters (natural frequencies, damping ratios and mode shapes) of a structure from measured (experimental) or simulated (finite elements modelling) vibration data [8]. This modal analysis can be done either in frequency, time or time-frequency domains. When working in the frequency domain, in our case, the determination of the frequency response functions (FRFs) is a required step for the determination of the dynamic parameters. The FRFs are defined as the output to input ratio; the output being the displacements in this case and the input is the force. After determining these FRFs, through mathematical and numerical tools of curve fitting, the dynamic parameters can be extracted, highlighting the need of accurate and less noisy FRFs data. Among these tools of curve fitting used to extract dynamic parameters from FRFs data, there are the well-known and simplest peak-picking method, the circle-fitting method, the global rational fraction polynomial (GRFP) [9], etc. A review of these modal analysis methods can be found at [6, 10].

In this paper, the circle-fitting method is applied to extract dynamic parameters from FRFs as it shows accurate results for a large number of situations [10, 11] and is easily implemented. This method requires also minimum computer resources, it gives better results than other methods such the peak-picking one and is not as sensitive to effects from adjacent modes [12]. This method is based on the fact that the Nyquist plot of the imaginary part vs the real part of an FRF in the vicinity of one resonance (hence its classification in SDoF-Single Degree of Freedom methods) gives a circle-like graph. The fitting of this circle-like graph gives the dynamic parameters [13, 14]. The main drawback of this method is that, even though it can give satisfactory results, it is very time-consuming when one has many FRFs to analyze.

16.3 Experimental Setup

As stated above, a seven-wire strand has been used; a seven meters long specimen of which is mounted on a load test rig as shown in Fig. 16.1a.

Anchor wedges, at both ends, fix the cable to the load test rig. Transient impulses are applied to the cable using an impact hammer equipped with a force transducer (Fig. 16.1c). The tension of the cable is applied using a hydraulic cylinder on which there is a force gauge to measure the force (Fig. 16.1b).

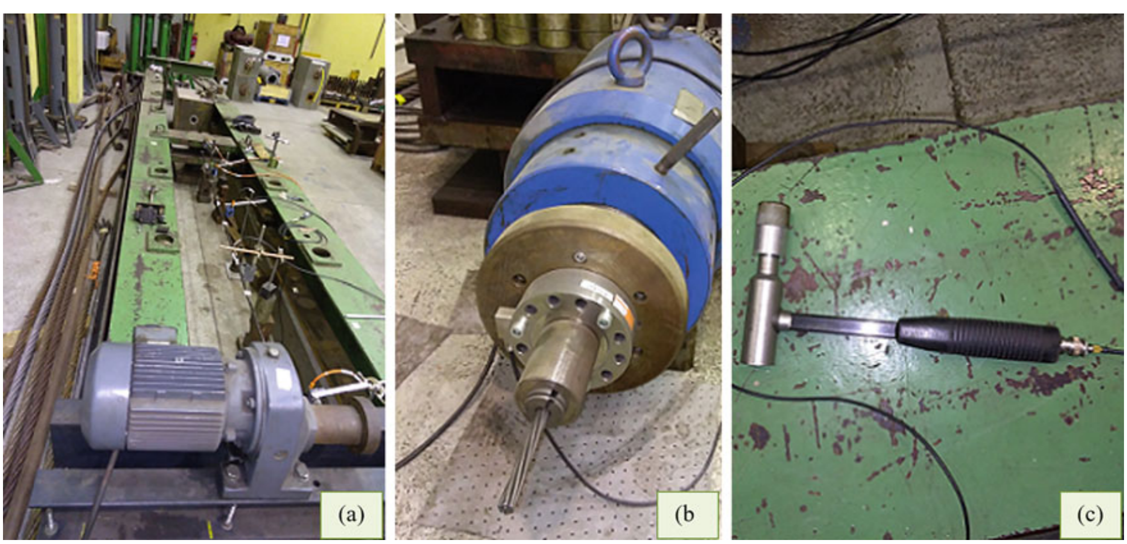

Fig. 16.1 Testing means – (**a**): load test rig with seven-wire strand and sensors, (**b**): anchor and hydraulic cylinder, (**c**): impact hammer

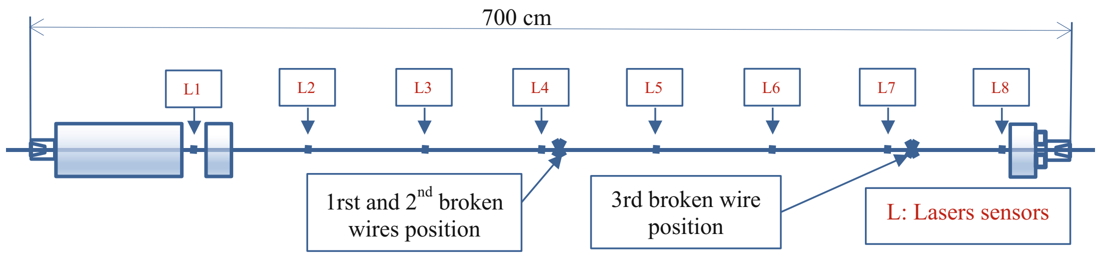

Fig. 16.2 Tests layout

For the data acquisition and storage, laser sensors have been used. The laser sensors give the cable's displacements that are used for the determination of its dynamic characteristics. These lasers are coupled with Quantums MX 1615B and 1610 data acquisition systems. The CATMAN software is used for the visualization of the data. A temperature probe is also used to monitor temperatures variations all along the tests.

Baring in mind that the aim of the tests is to characterize damages in the seven-wire strand, the tests are done on a safe cable and a damaged one with different levels of damages. The damages are introduced in the strand by cutting one, two and three wires gradually. The positions of these damages are represented on Fig. 16.2 that shows also the laser sensors layout. The tests procedure can then be summarized in these seven steps:

1. Tensioning of the cable: the seven-wire strand is taut at 30% of its breaking load
2. Mounting the lasers and the data acquisition systems. To ensure the functionality of these devices some preliminary tests are done. The lasers are placed so that those with the larger measuring ranges are placed in the middle and the others to the ends in order to record all the displacements during the vibration of the cable
3. Excitation of the cable by hammer impact. Near each laser position, the impact is repeated seven times in order to measure data repeatability. The data (cable displacements) given by laser sensors are stored at the sampling rate of 300 Hz during 45 s
4. First wire break: the position is indicated on Fig. 16.2. After this first damage, there is a loss of tensile strength and the cable is not retaut at its first tension value but left as is
5. We repeat steps 2 and 3
6. Introduction of second wire break at the same place than the previous one and we repeat the same tests
7. Introduction of the third wire break near to the anchorage and repeat of the same tests.

16.4 Results Analysis

16.4.1 Damage Detection and Location

To detect and locate damage, vibration-based comparison between cables of different states of safety is done through their dynamic characteristics (natural frequencies, damping ratios and mode shapes). The comparison between safe strand and the strand with one broken wire is then done. To determine the dynamic characteristics, one calculate at first the FRFs since both input and output data are available by using the hammer impact. In Fig. 16.3, the Bode diagrams (phase and amplitude vs frequency) of receptance are plotted. The name 'receptance' is used for FRFs when the output is the displacements. Are only presented in Fig. 16.3, the FRFs obtained with impact at position L1 (see Fig. 16.2) and response at the same position. To lighten the text, the Bode diagrams of the others FRFs are not presented, but they are similar to the one plotted.

An analysis of both FRFs of safe and damaged cables shows that, even though the changes in phases are not very clear (due to the fact that they are very sensitive to noise) [8], the first three resonance peaks, corresponding to location of natural frequencies, are well separated. From the fourth resonance, the peaks are less clear and the level of noise become important. Up to this point of the analysis, the only difference noticed between the two graphs is that the peaks resonances of the damaged cable happen at lower frequency values. Thus, for a more complete comparison between the two states of the cable, one have to determine the dynamic parameters.

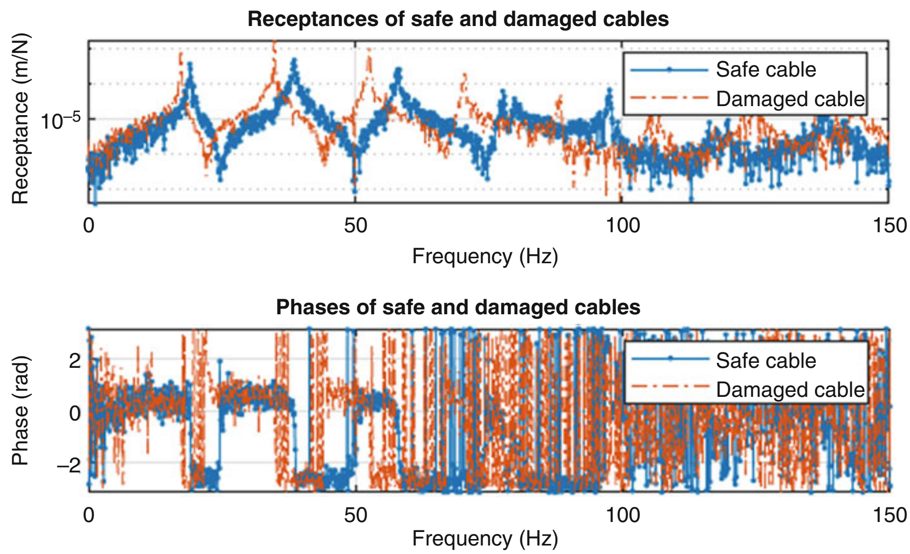

Fig. 16.3 Bode diagrams of safe and damaged cables

Table 16.1 Comparison of safe and damaged cables natural frequencies.

	Safe cable		Damaged cable		
Modes	$f_n^s(Hz)$	$CV^s(\%)$	$f_n^d(Hz)$	$CV^d(\%)$	$C_i(\%)$
1	19.16	0.42	17.47	0.18	8.84
2	38.65	0.14	34.68	1.47	10.27
3	58.08	0.18	52.65	0.26	9.35
4	78.06	1.08	70.46	0.13	9.74
5	97.60	0.08	88.39	0.15	9.44

Based on these FRFs curves, the cables dynamic parameters calculation is done. This step is carried out using the circle-fitting method. Natural frequencies and mode shapes are then calculated and used to detect, locate and estimate damage severity in the cable.

Detection

For each hammer impact, the natural frequencies for the two cables are calculated; the mean values with the coefficients of variation are given in Table 16.1. The coefficient of variation is obtained by dividing the standard deviation (std) by the average (mean):

$$CV\ (\%) = 100 * \frac{std\ (f_n)}{mean\ (f_n)} \tag{16.1}$$

The analysis of this Table 16.1 shows that the natural frequencies have decreased for all modes. Since natural frequencies are easily determined, in fact they can be determined directly through FRFs or Fourier transforms plots given by one sensor, and are less affected by experimental errors [15], they are used for the damage detection. To do so, the percentage of changes in natural frequencies, C_i (%) [16, 17], is calculated and the values are included in Table 16.1. This damage indicator is calculated as:

$$C_i\ (\%) = \frac{f_n^s - f_n^d}{f_n^s} \tag{16.2}$$

Where f_n^s and f_n^d are natural frequencies of respectively safe and damaged cables.

It can be noticed that all the values of C_i are higher than 8%. Taking into account that the errors in natural frequencies values for both states (safe and damaged) are very low (CV < 1.5% for all of them) compared to those of C_i, one can conclude that the values of C_i > 8% indicate that there is a damage in the structure, i.e. the cable. Moreover, these values of the C_i parameter are superior to 5%, the threshold above which one can attribute changes in natural frequencies to damage in structures [18]. Interestingly enough, this parameter is only based on natural frequencies that can be obtained through the data given by only one sensor. Thus in a practical case, there is no need of a "sophisticated" instrumentation to show that there is defect, hidden or not, in structures. However, to further the analysis, it shall be interesting to indicate the location of the defect in the cable. Based only on the C_i parameter, this goal comes out unfulfilled since it does not include a spatial parameter in its expression to locate the damage. For this reason, the *MCD* (Modal Curvatures Differences) [19] parameter is used for the purpose.

Location

The *MCD* parameter is based on the curvature mode shapes (ϕ'') which are given from the mode shapes displacement (ϕ) by using central difference approximation [20]:

$$\phi''_{q,i} = \frac{\phi_{q,i-1} - 2*\phi_{q,i} + \phi_{q,i+1}}{h^2} \tag{16.3}$$

Where q is a degree of freedom (DoF), $\phi_{q,\,i}$ is the displacement mode shape of the mode i at DoF q and h is the mean distance between DoFs (sensors). For the determination of ϕ'' at first and last DoFs (the end points), respectively the first and last addends of the numerator are considered zero values. Consequently, this can introduce some inaccuracies in these values of ϕ'' at end points.

The *MCD* factor is then calculated by the absolute difference of the curvature mode shapes (ϕ'') between safe and damaged cables:

$$MCD_{q,i} = \left| \left(\phi^s_{q,i}\right)'' - \left(\phi^d_{q,i}\right)'' \right| \tag{16.4}$$

This damage indicator should have a maximum value at the position of a damage. Thus, for the impact next to L1 (laser 1) (see Fig. 16.2 for the position), the *MCD* values for the first mode are plotted at the Fig. 16.4 below.

In this Fig. 16.4, it can be noticed that the damage is located near to its exact position shown by the asterisk. In fact, using MCD values, the less accurate location is lower than one meter. These results show that the *MCD* values obtained with the curvature mode shapes of mode 1 are a good mean to localize the damage in the cable. The maximum values noticed at DoF 1 for the impact at L2 (laser n°2) and L5 (laser n°5) can be explained by the fact that the calculation of curvature mode shapes (ϕ'') is not always exact at end points, as noticed earlier.

16.4.2 Estimation of Damage Severity

In the previous section, the damage characterized by one broken wire is detected and located by using C_i and *MCD* factors. To give a factor estimating the damage severity, one has to consider also the cable with different levels of damage. This is achieved in our case by two and three broken wires in the seven-wire cable. As the C_i factor is based on natural frequencies which can be *easily* determined and are less effected with experimental errors, a mean of estimation of damage severity based on it comes out interesting for fast evaluation of structures safety.

Thus, the natural frequencies of the cable with respectively two and three broken wires are calculated. The calculation of the natural frequencies is based only on the peak of Fourier transforms (FTs) of displacements. To show the relevance of using FTs, the natural frequencies of safe cable are recalculated based on FTs peaks and compared with those given in Table 16.1 that are obtained using circle-fitting method on FRFs. The result is given in Table 16.2 and show the almost equivalence of the two methods *in finding natural frequencies* as the differences are very low (inferior to 0.2%).

Thus, the determined natural frequencies of cable with two and three broken wires are given in Table 16.3.

The results in this Table 16.3 show that by increasing the level of the damage (number of broken wires), the values of natural frequencies decrease. This decrease in natural frequencies results in an increase in the C_i factor. The percentages of change in natural frequencies (C_i) are calculated for the cable with two and three broken wires and the values are compared with those of one broken wire, see Fig. 16.5. For one state of the cable (one specific level of damage), the C_i parameter is almost constant regardless of the chosen mode. Given the fact that, for the location of the damage with *MCD* factor, the

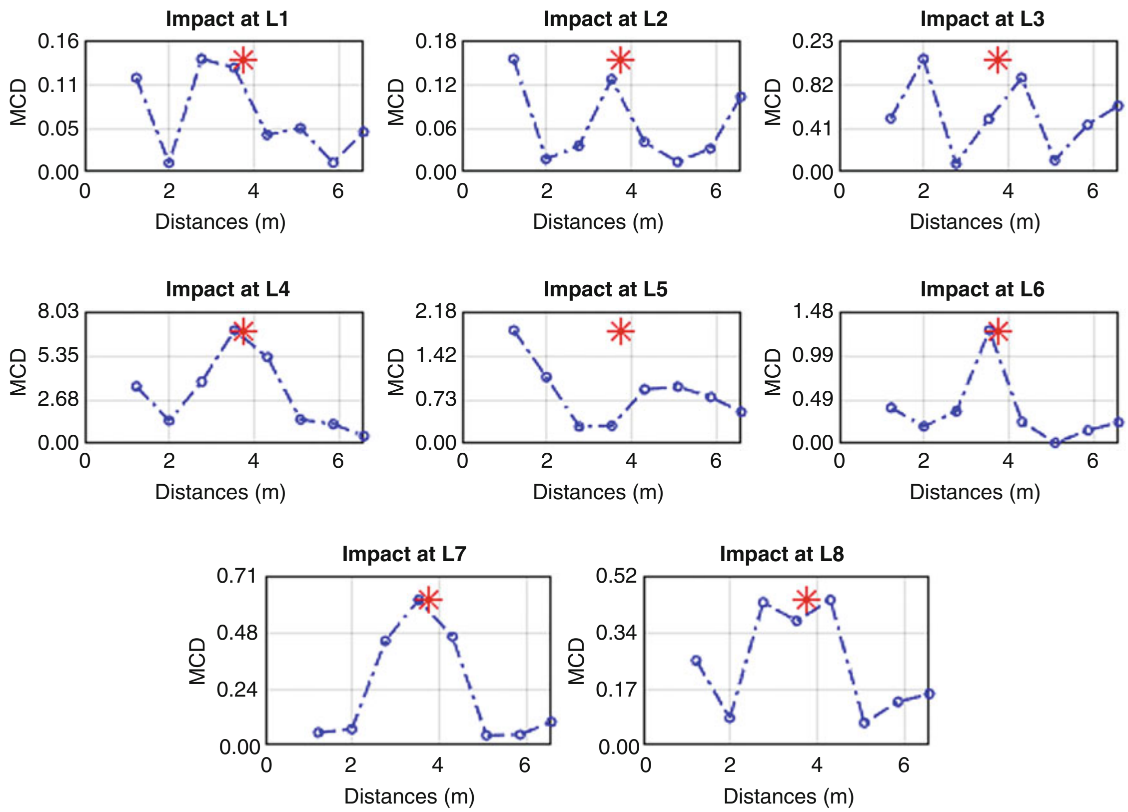

Fig. 16.4 MCD values based on the curvature mode shapes of mode 1

Table 16.2 Natural frequencies of safe cable obtained with TFs and FRFs.

Modes	$f_n^s(Hz)$ with FRFs	$f_n^s(Hz)$ with TFs	Difference (%)
1	19.16	19.19	0.16
2	38.65	38.64	0.03
3	58.08	58.14	0.10
4	78.06	77.95	0.14
5	97.60	97.48	0.12

Table 16.3 Natural frequencies of cables with 2 and 3 broken wires

	Cable with 2 broken wires			Cable with 3 broken wires		
Modes	$f_n^{d2}(Hz)$	$CV^{d2}(\%)$	$C_i^{d2}\ (\%)$	$f_n^{d3}(Hz)$	$CV^{d3}(\%)$	$CV_i^{d3}\ (\%)$
1	14.56	0.18	24.14	11.49	0.16	40.13
2	29.08	4.03	24.74	23.03	0.12	40.39
3	43.99	0.16	24.34	34.65	0.26	40.40
4	58.55	2.38	24.89	45.96	3.69	41.03
5	73.28	2.78	24.82	56.51	6.44	42.03

results obtained with the mode 1 best locate the defect, for the damage severity, the C_i parameters calculated with the first natural frequencies will be used.

The C_i values (for the first natural frequency) for the three levels of damage are respectively 9.08%, 24.14% and 40.13%. For comparison, the mean values based on the five natural frequencies are 9.56%, 24.59% and 40.8% respectively.

The damage severity can be expressed directly as the percentage of broken wires over the total wires of the cable. Thus, we define the factor *DS* (Damage Severity) as:

$$DS\ (\%) = 100 * \frac{Number\ of\ broken\ wires}{Total\ of\ wires} \tag{16.5}$$

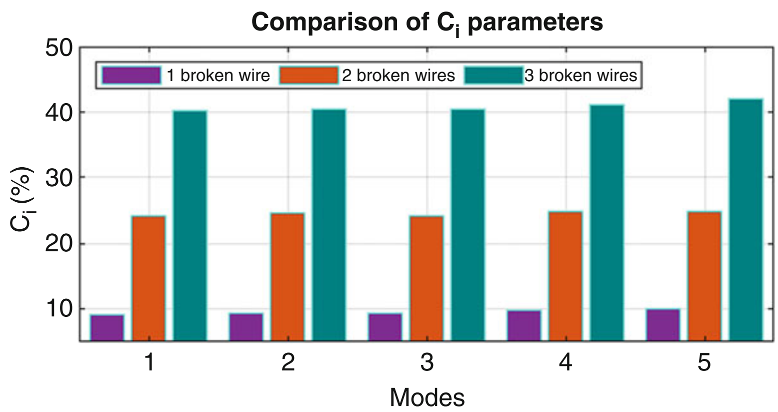

Fig. 16.5 Comparison of Ci parameters for the three levels of damages in the cable

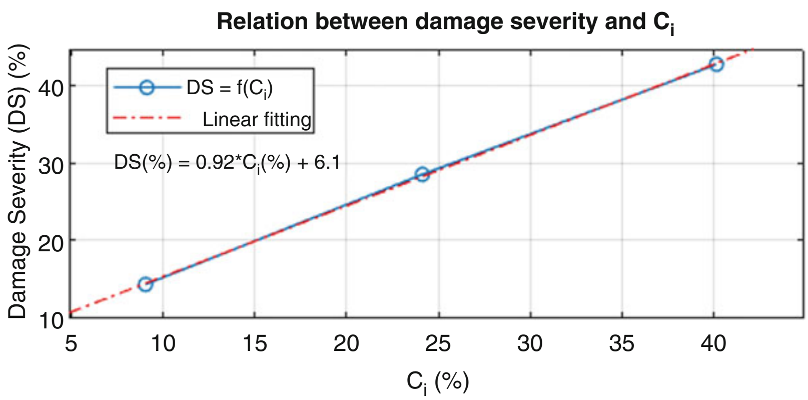

Fig. 16.6 Estimation of damage severity with Ci parameter

In this current study, the values of *DS* are then 14.29%, 28.57% and 42.86% for respectively one broken wire, two broken wires and three broken wires.

To establish a relation between the C_i parameter and the damage severity, in the Fig. 16.6 one has the *DS* parameter as a function of C_i parameter. It can be noticed that there is, for these three levels of damage, a linear relation between the C_i parameter and the damage severity (*DS*) as $DS(\%) = 0.92C_i(\%) + 6.1$. Thus, this relation gives an easy and fast way to estimate the damage severity in cables. This relation also defines a detection threshold of 6.1%; i.e. the damage severity is detectable when the C_i parameter is greater than 6.1%, which agrees with the result found for the cable with one broken wire.

16.5 Conclusion

Using a hammer impact excitation, the detection, location and damage severity estimation on a seven-wire strand have been done. As the hammer with a force transducer gives the input force and laser sensors the displacements of the strand, the FRFs (Frequency Response Functions) are used to calculate the cable's dynamic characteristics by the mean of circle-fitting algorithm. Through the changes in natural frequencies, the C_i parameter constitutes an efficient way to detect damage in cables. Since it cannot give the position of the damage, it is combined with the *MCD* parameter that locates the damage with more accurate results when it is based on the first curvature mode shapes. Hence, the damage severity estimation is developed based on the first natural frequencies variation for three different levels of damage in the cable. This way of determining the damage severity through the C_i parameter, based only on the variations of first natural frequencies, constitutes and easy, though robust, way to characterize *safety of* ***cables***.

Thus, practically, only one sensor can be used to determine natural frequencies in order to evaluate structures (cables) safety by the mean of the *DS* parameter. According to a fixed threshold of the *DS* parameter, the investigation can be furthered using a given number of sensors to locate the damage (through the *MCD* parameter) and repair it if necessary when this threshold is exceeded. Therefore, practitioners or project owners can use simple and light means to monitor structures and know when to intervene and take out reparative action.

To validate this approach of characterizing damages in cables, further steps can be taken. At first, the detection of the damage by the *MCD* parameter should be tested when the damage is near the anchors (for example the third damage introduced in the strand). In addition, the calculation of the *DS* parameter by the C_i parameter is to be validated with multilayer cables where a broad range of damage severity can be tested by cutting many wires gradually.

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