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# Effects of the concrete damage due to corrosion of steel bars on the static and dynamic response of PRC/RC beams

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The products of steel corrosion create volumetric expansion in the steel bars causing extremely high tensile forces within the concrete .

In reinforced (RC) and pre-stressed reinforced concrete (PRC) beams, damage due to reinforcement corrosion appears as cracks both in the tensile zone of bending and in the compressive zone.



(a)

side 1

side 2

(b)

side 1

coated steel bars

side 2
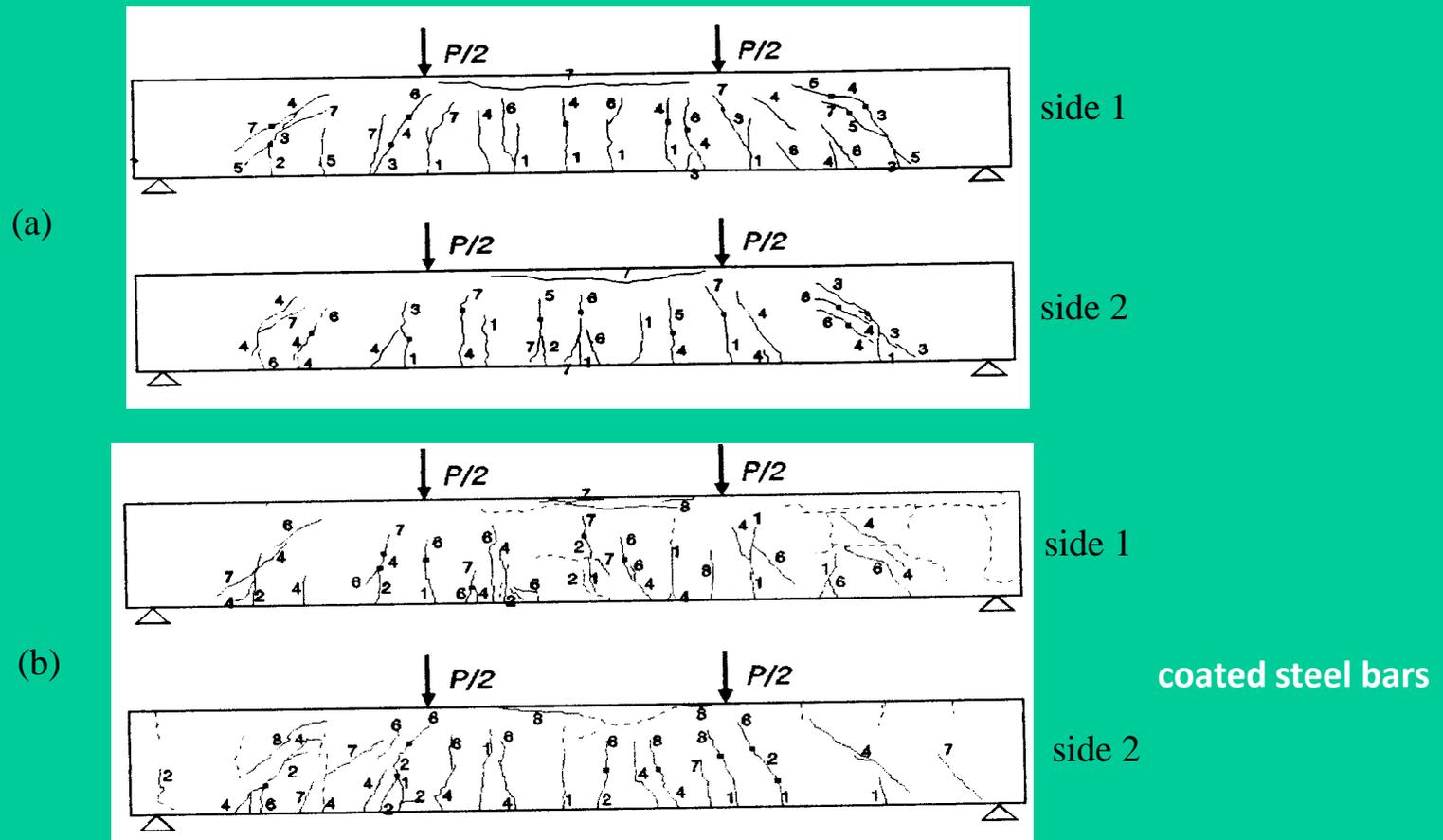
# Undamaged RC Beam under bending tests
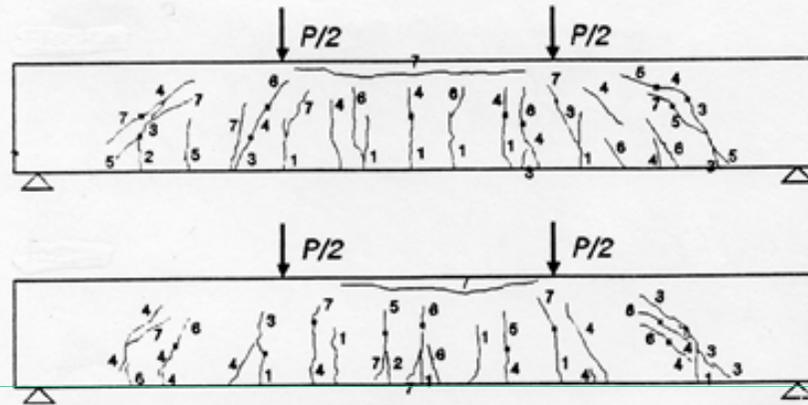


| Data di confezione | 12.10.88 |
| Data di prova | 03.03.92 |
| a/c | 0.4 |
| Armatura | 8 φ 12 |
| Copriferro δ (cm) | 2 |
| Stagionatura | Atmosfera |

Undamaged RC beam Concrete w/c=0.4

PIL 8: quadro fessurativo. Valgono le stesse convenzioni grafiche utilizzate per il rilievo di PIL 1. Per i carichi di inizio ricognizione si ha invece:

1. $P > 50$ KN    4. $P > 125$ KN    7. $P > 200$ KN
2. $P > 75$ KN    5. $P > 150$ KN
3. $P > 100$ KN    6. $P > 175$ KN.
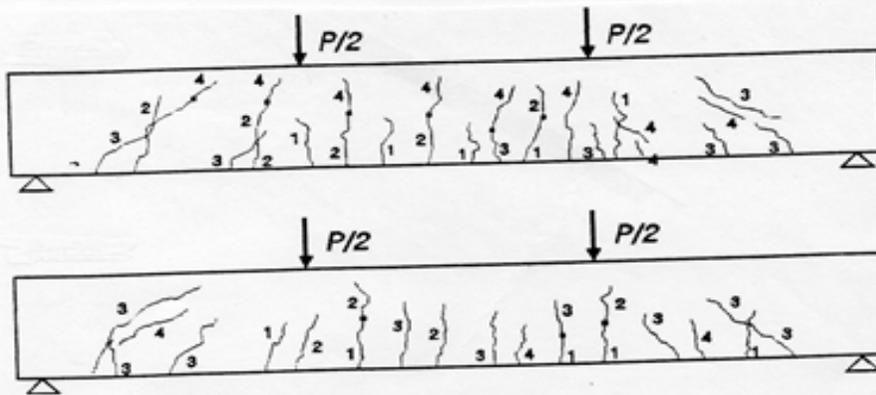
# Damaged RC Beam under bending tests
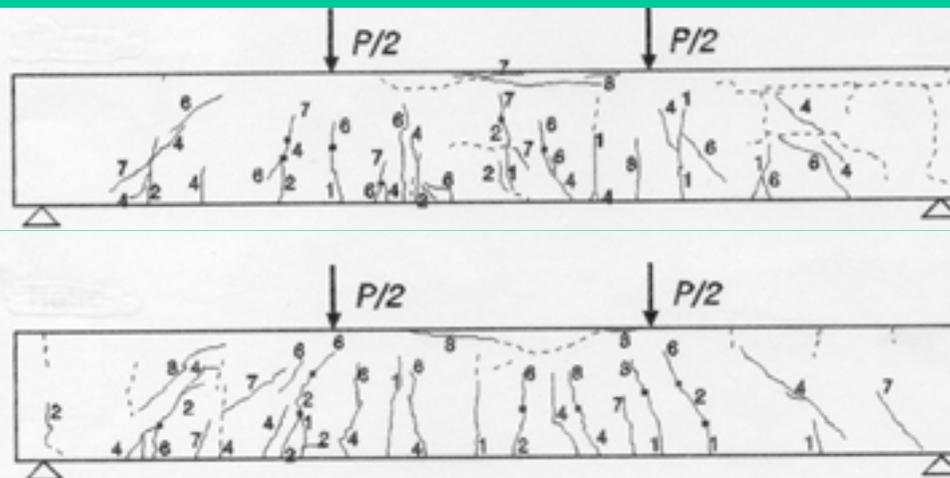


PIL 4: quadro fessurativo. Valgono le stesse convenzioni grafiche utilizzate per il rilievo di PIL 1. Per i carichi di inizio ricognizione si ha invece:

1. $P > 50$ KN    4. $P > 125$ KN    7. $P > 187$ KN
2. $P > 75$ KN    5. $P > 150$ KN    8. $P > 200$ KN
3. $P > 100$ KN    6. $P > 175$ KN.

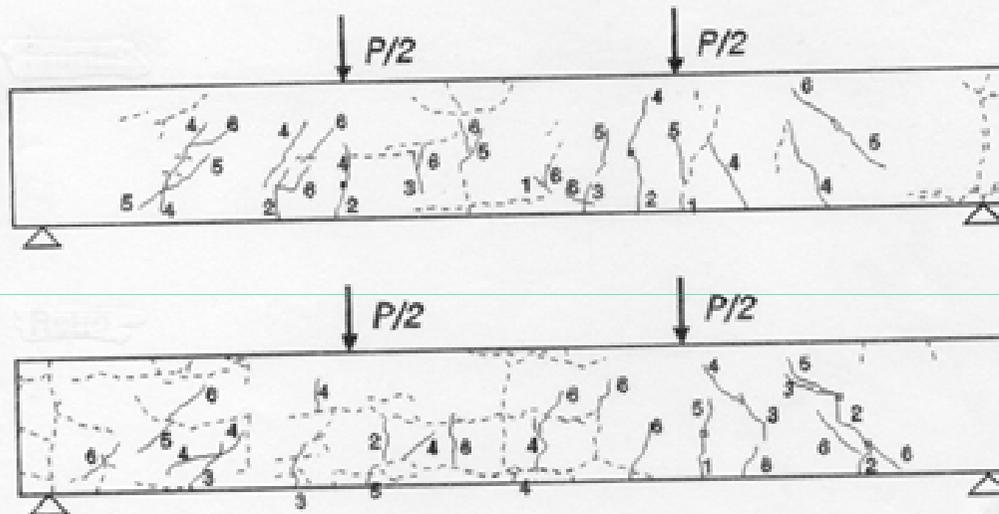| | |
|---|---|
| Data di confezione | 14.10.88 |
| Data di prova | 05.06.92 |
| $a/c$ | 0.6 |
| Armatura | $8 \phi 12$ |
| Copriferro $\delta$ (cm) | 2 |

Undamaged
RC beam
Concrete w/c=0.6

PIL 16: quadro fessurativo. Valgono le stesse convenzioni grafiche utilizzate per il rilievo di PIL 1. Per i carichi di inizio ricognizione si ha invece:
1. $P > 50$ KN        4. $P > 175$ KN
2. $P > 100$ KN
3. $P > 150$ KN

Damaged RC Beam under bending tests



PIL 2: quadro fessurativo. Valgono le stesse convenzioni grafiche utilizzate per il rilievo di PIL 1. Per i carichi di inizio ricognizione si ha invece:
1. $P > 50$ KN        4. $P > 125$ KN
2. $P > 75$ KN        5. $P > 150$ KN
3. $P > 100$ KN       6. $P > 175$ KN.

4

**Cracks due to rust create a compressive softening effect in the concrete thus influencing strength, ductility and load-deflection response of the beam.**

**On the basis of experimental moment-curvature diagrams a coefficient of damage in the elastic field may de defined comparing the response of undamaged (U) and damaged (D) beams by bending stiffness**
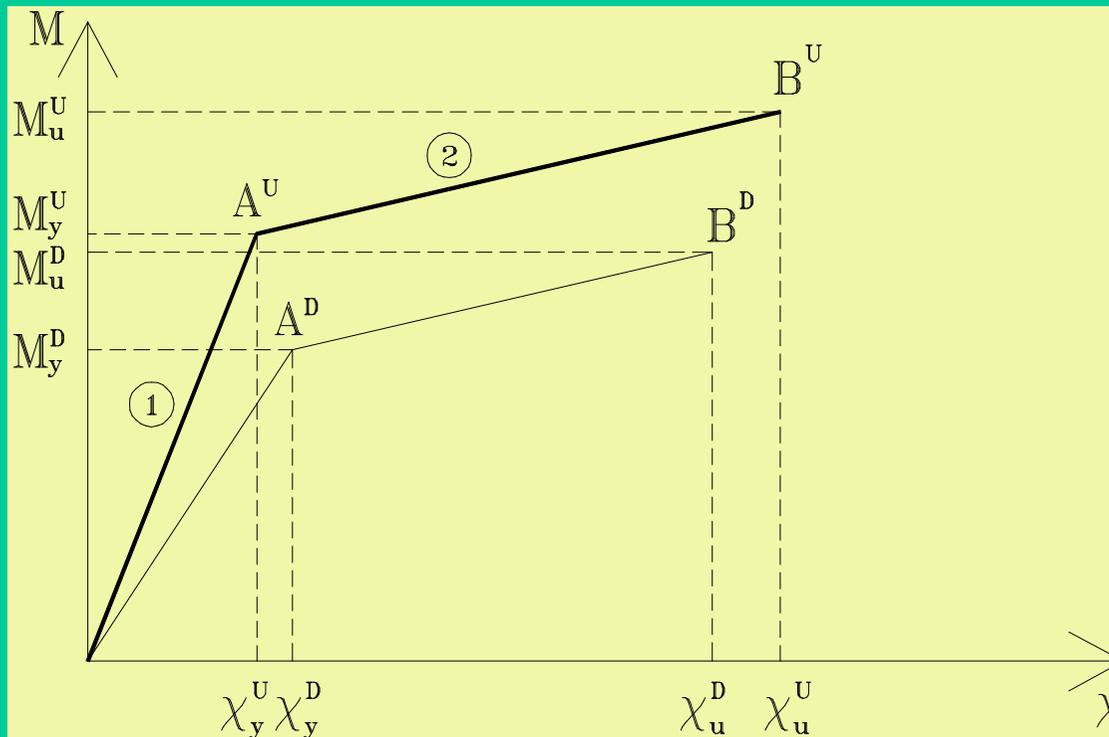


$$DC = 1 - \frac{EI_1^D}{EI_1^U}$$

$$\chi_1^D = \frac{\chi_1^U}{1 - DC}$$

$$DC = 1 - (\frac{f_r^D}{f_r^U})^2$$

# Objectives

## The present paper reports on experimentally investigation through
## dynamic and static tests on PRC and RC beams undamaged and damaged by corrosion of steel bars.
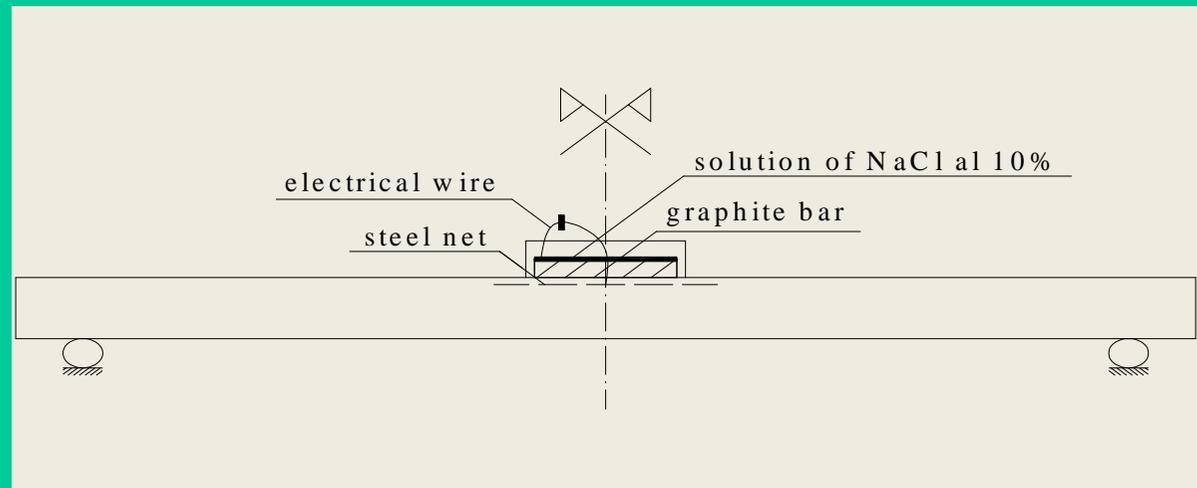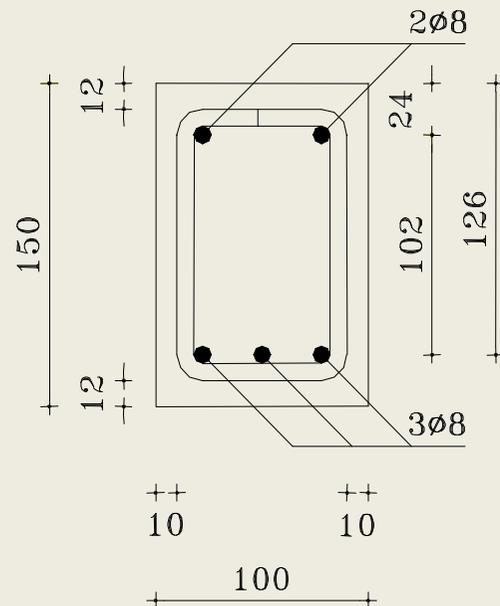
The experimental program foresees PRC/RC beams subjected to artificial reinforcement corrosion and successively to static loading with increasing applied loads to produce bending cracking.
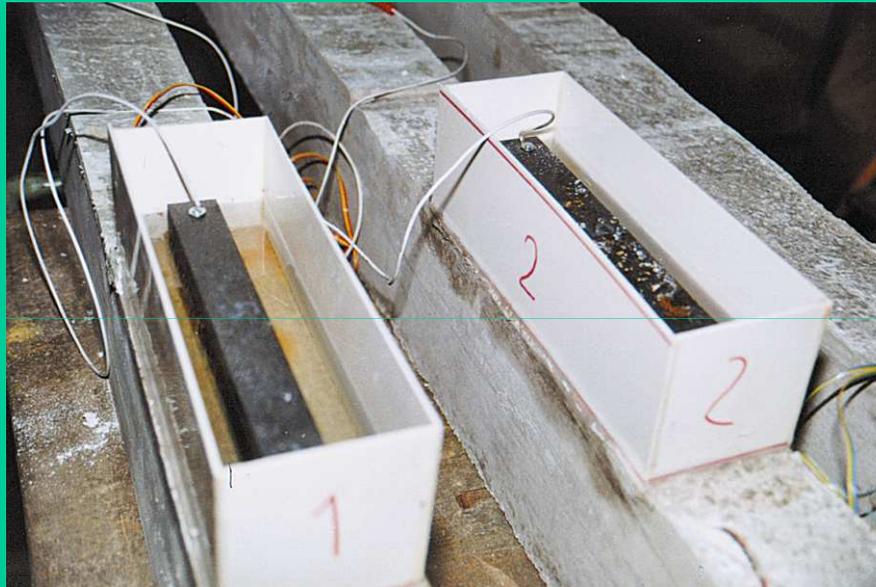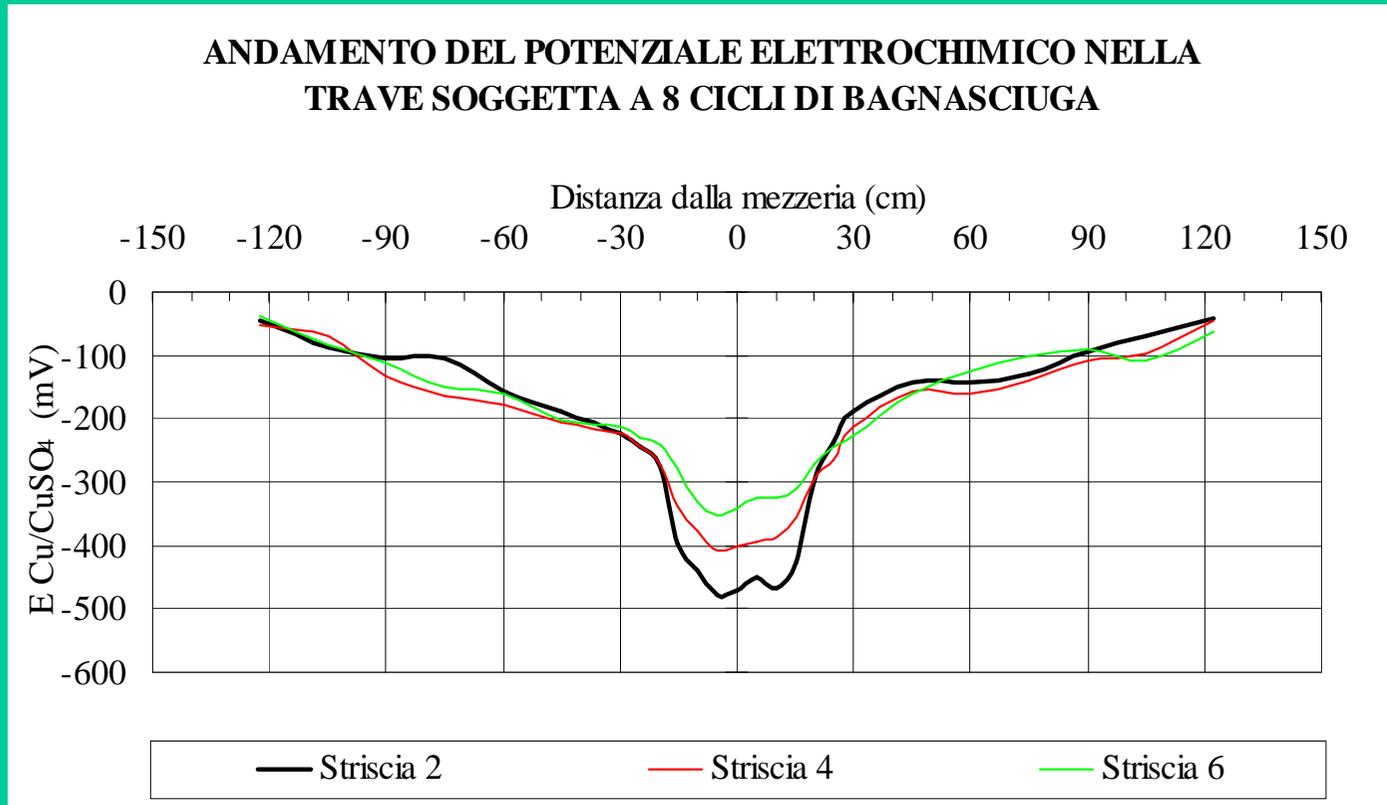


Dynamic investigation was developed both on undamaged and damaged PRC/RC beams measuring natural frequencies and evaluating vibration mode shapes.

# A- Experimental response of RC beams damaged by corrosion

1. Three RC beams (B1, B2 and B3) were experimentally tested.

2. The beams have a rectangular reinforced section with the length L=2.45m.

3. A steel net is positioned in the middle of the beam.

4. Two beams - B2 and B3- have been subjected to cycles of accelerated corrosion through the combined action of a sodium chloride solution (NaCl at 10% of concentration) and a graphite bar electrically joined to the steel reinforcement .

# Measures of electrochimical potential



ANDAMENTO DEL POTENZIALE ELETTROCHIMICO NELLA TRAVE SOGGETTA A 8 CICLI DI BAGNASCIUGA

**Free vibration frequencies were measured for beam B1, undamaged beam, and B2 and B3, subjected to the corrosion cycles. During the dynamic tests, the beams were hung by flexible springs that simulate the free-free conditions.**

**The beams were excited by an impulsive load given by an impact hammer, and the response was measured at different positions using accelerometers.**



Set-up for dynamic tests



impact hammer

**B1**
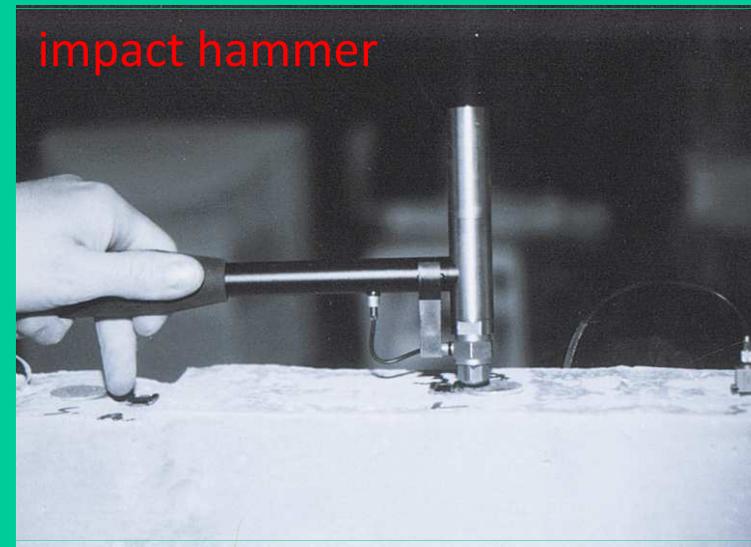
| Days* | $f_1$ (Hz) | $f_2$ (Hz) | $f_3$ (Hz) | $f_4$ (Hz) |
|-------|-----------|-----------|-----------|-----------|
| 34 | 57.50 | 183.17 | 371.33 | 563.00 |
| 70 | 57.71 | 182.40 | 368.50 | 559.40 |
| 83 | 57.33 | 182.58 | 370.50 | 559.92 |

**Frequency time variation in the undamaged model beam B1 is not significant.**

Experimental frequency values have been compared with theoretical values obtained by homogeneous Eulero-Bernoulli model of beam and FEM analysis.
The theoretical values were obtained by **circular natural frequency** values for generic mode **r** of vibration in the case of **both ends free.**

$$\omega_r^f = \left( a_r \cdot \frac{r\pi}{L} \right)^2 \cdot \sqrt{\frac{EI}{\rho A}}$$

| Method of analysis | $f_1$ (Hz) | $f_2$ (Hz) | $f_3$ (Hz) | $f_4$ (Hz) |
|---|---|---|---|---|
| Experimental beam model | 57.514 | 182.715 | 370.111 | 560.771 |
| Eulero-Bernoulli beam model | 84.466 | 234.628 | 454.630 | 760.195 |
| FEM | 84.141 | 228.752 | 432.644 | 676.705 |

Following Tables show the frequency measures at time varying for the first four vibration mode, respectively, for beam B2 and B3 by dynamic tests of vibration of beams with free-free ends.
In the Figure  the variation of  frequency values measured on beam B2 at time is shown.

# Frequency measures at time varying for the first four vibration mode, respectively, for beam B2 and B3 by dynamic tests of vibration of beams with free-free ends.

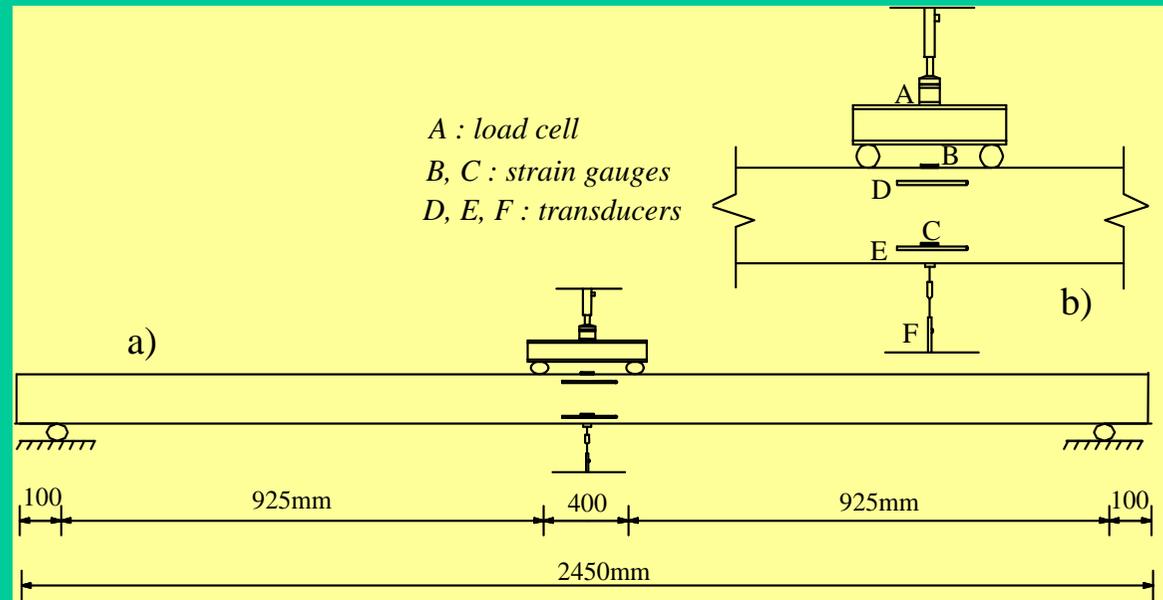## Experimental frequency values $f_1 \div f_4$ for beam B2.
* Days after construction of beam

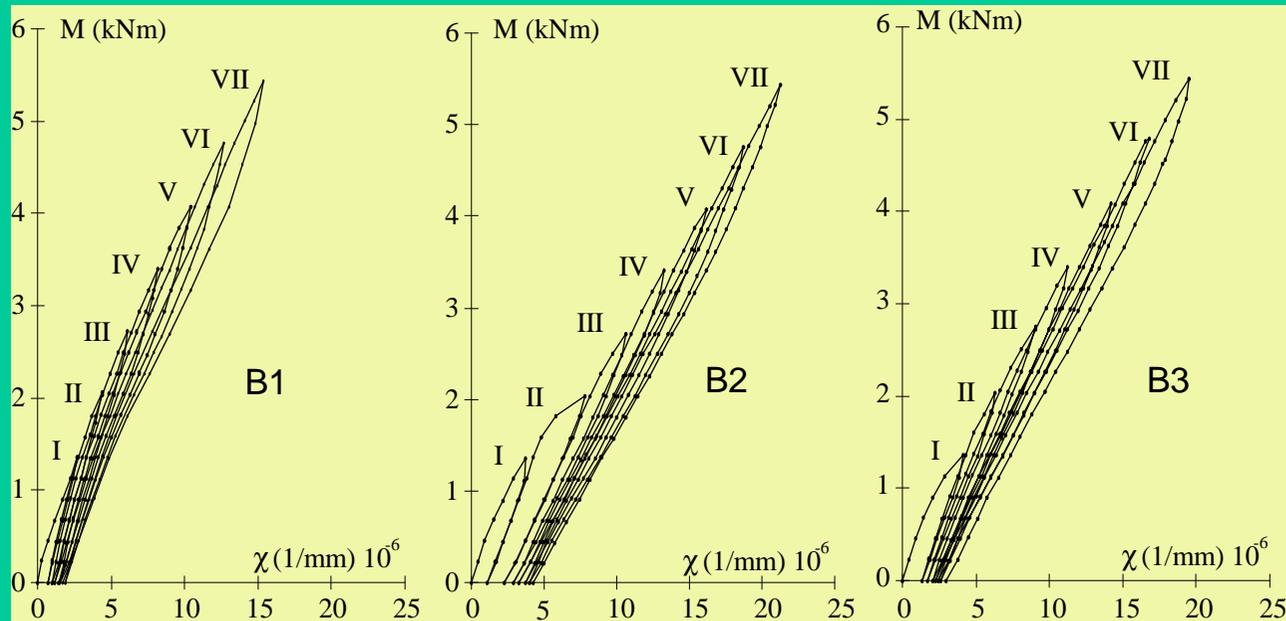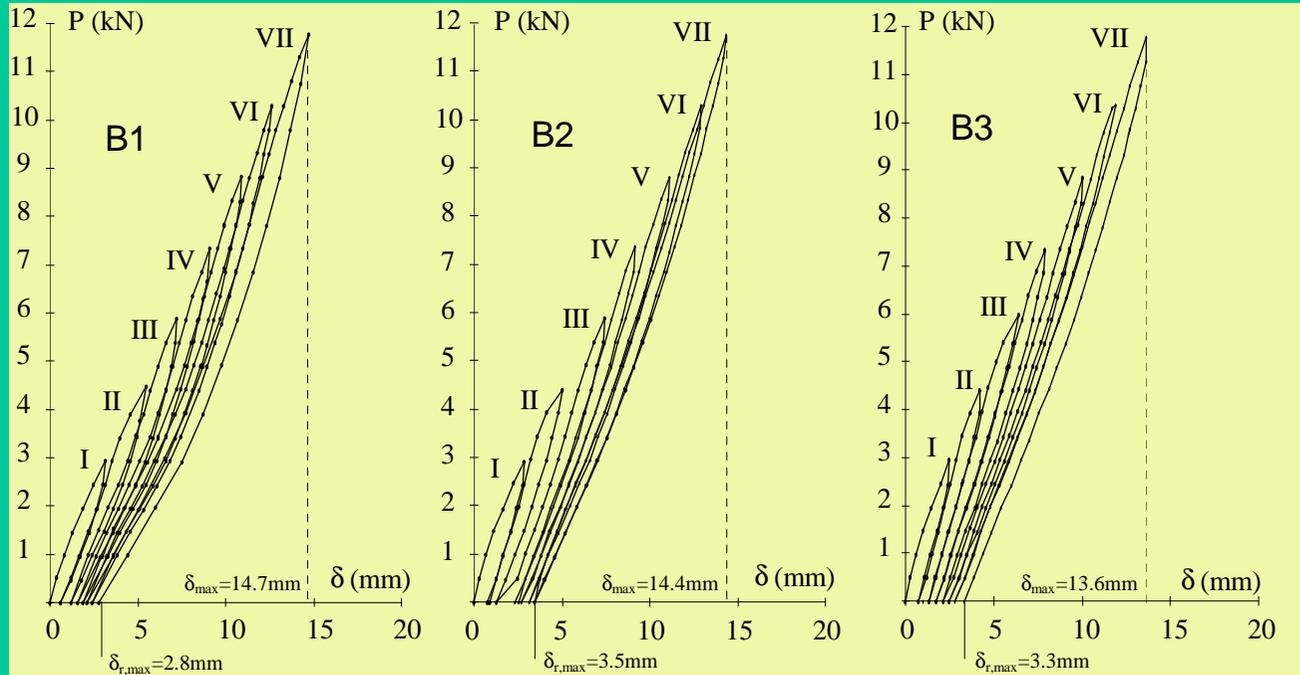| Days* | $f_1$ (Hz) | $f_2$(Hz) | $f_3$ (Hz) | $f_4$(Hz) |
|---|---|---|---|---|
| 56 | 82.916 | 224.416 | 435.833 | 683.667 |
| 57 | 82.833 | 223.833 | 435.500 | 681.167 |
| 63 | 81.958 | 221.875 | 431.958 | 674.333 |
| 74 | 80.000 | 216.958 | 423.083 | 661.000 |
| 84 | 74.916 | 203.333 | 408.583 | 639.5833 |
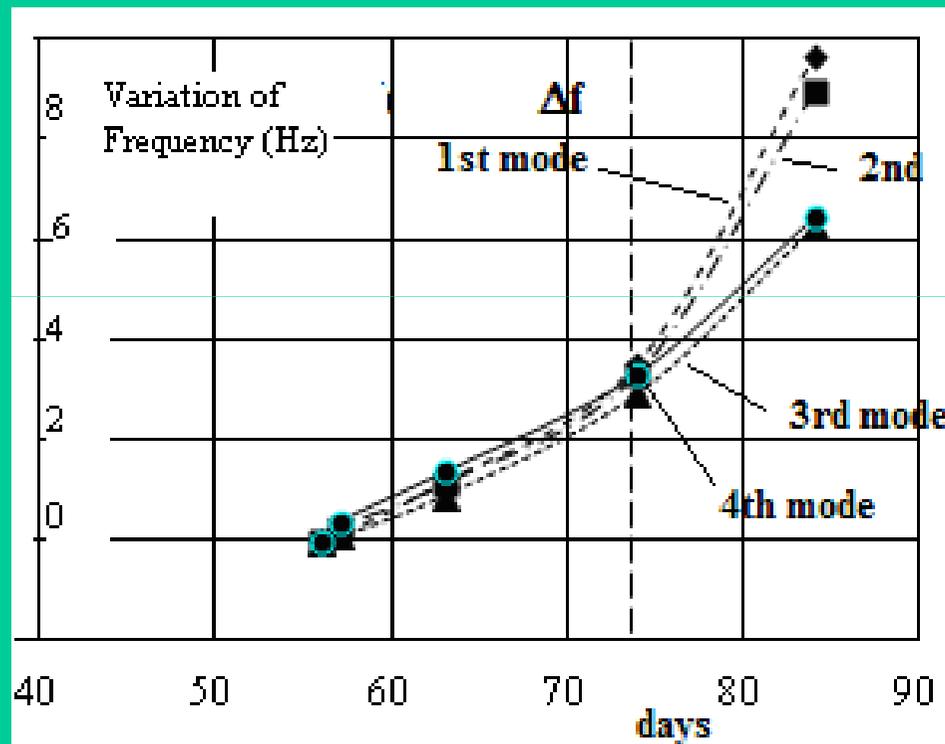


Variation of exp. frequency values for **beam B2 damaged** by corrosion.

# Static bending test of B1 (undamaged) and B2 and B3 (damaged beams)



A : load cell
B, C : strain gauges
D, E, F : transducers

a)

b)

100   925mm   400   925mm   100

2450mm

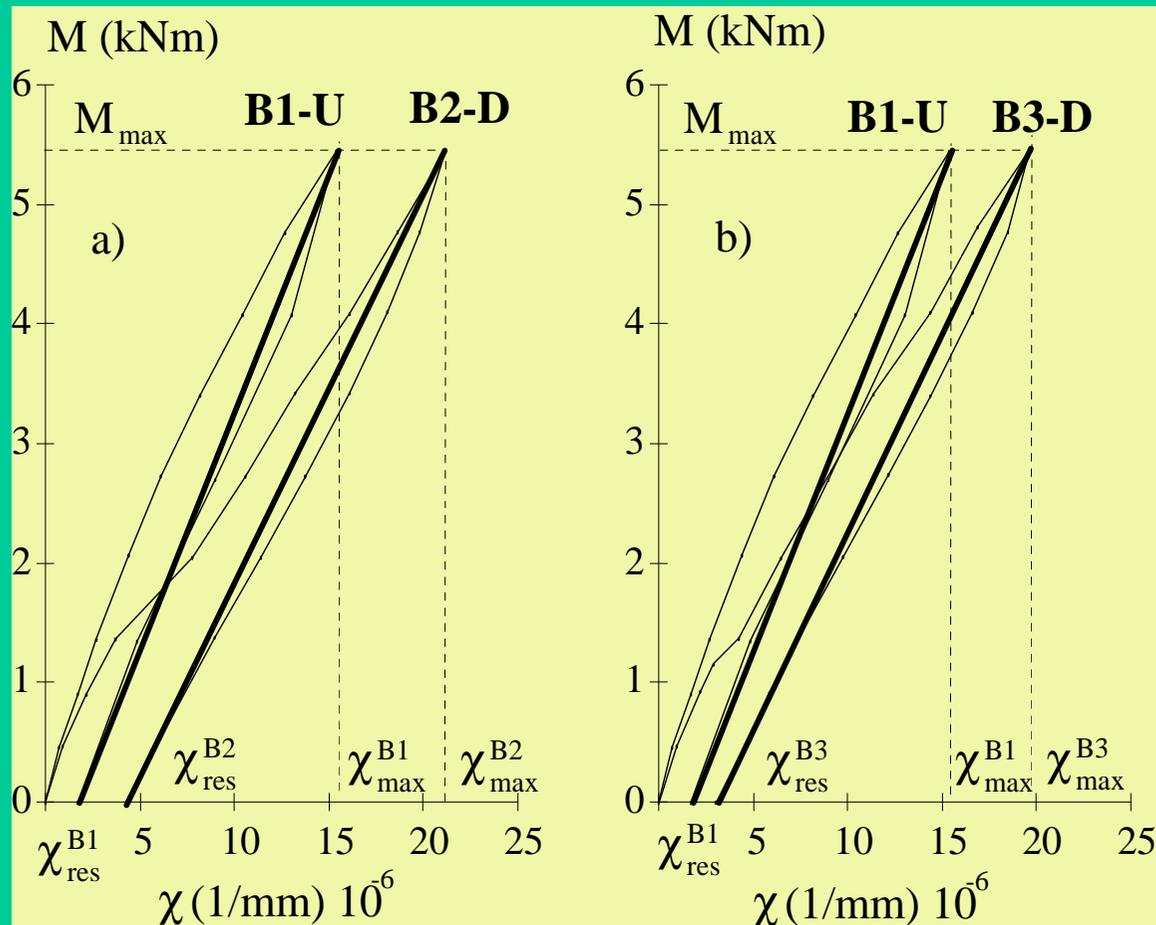# Experimental results from static bending tests on rc beams

The values of curvatures of B2 and B3 are higher than those for undamaged beam B1 .

Assuming an ideal straight lines for experimental moment vs curvature diagrams, the coefficient of damage may be evaluated:
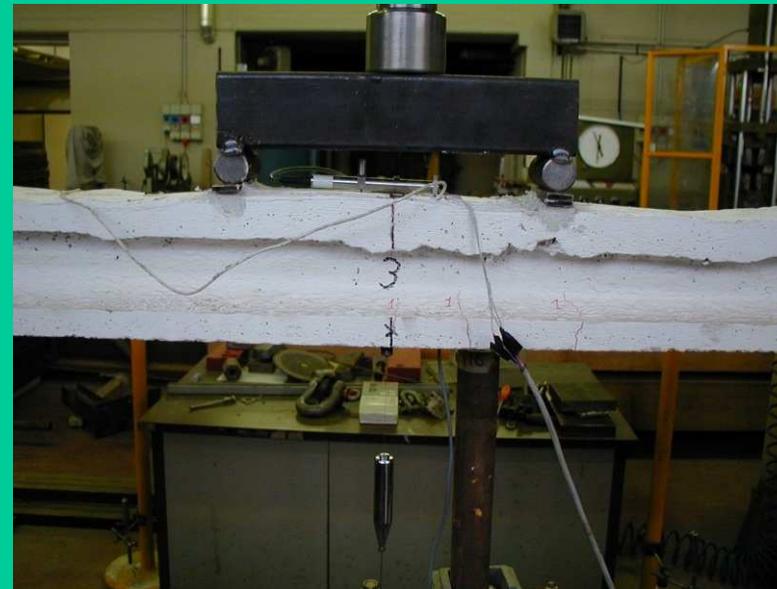
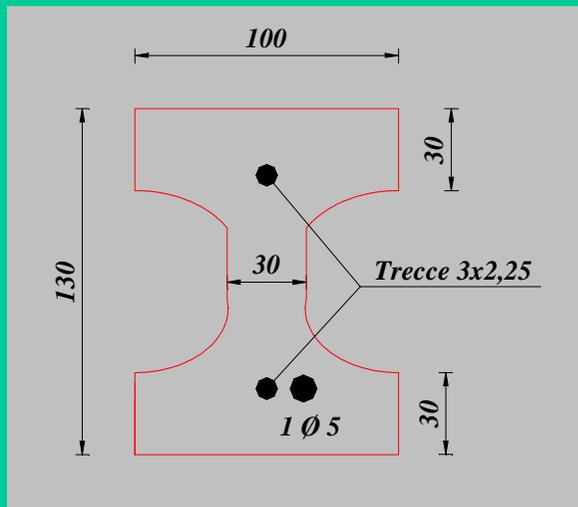DC = 0.20 for beam B2;

DC = 0.18 for beam B3.

# B - Experimental response of PRC beams damaged by corrosion

**Experimental research three beams were tested: B0-B1-B2**
**B0 under bending test;**
**B1 and B2 under bending and dynamic tests.**
The dimensions of double T section were: 100x130mm, respectively, for base and height; 30mm for width. The length of the beams was 2.45m .



Damage in PRC beam B2 was due to steel corrosion obtained in the same way described above for RC beams utilizing an artificial electrochemical process.
**Beam B2 was subjected to a corrosion through three artificial corrosion cycles for a period of 3 months from its construction.**
**Both beams B1 and B2 were successively tested by bending with the following load path.**
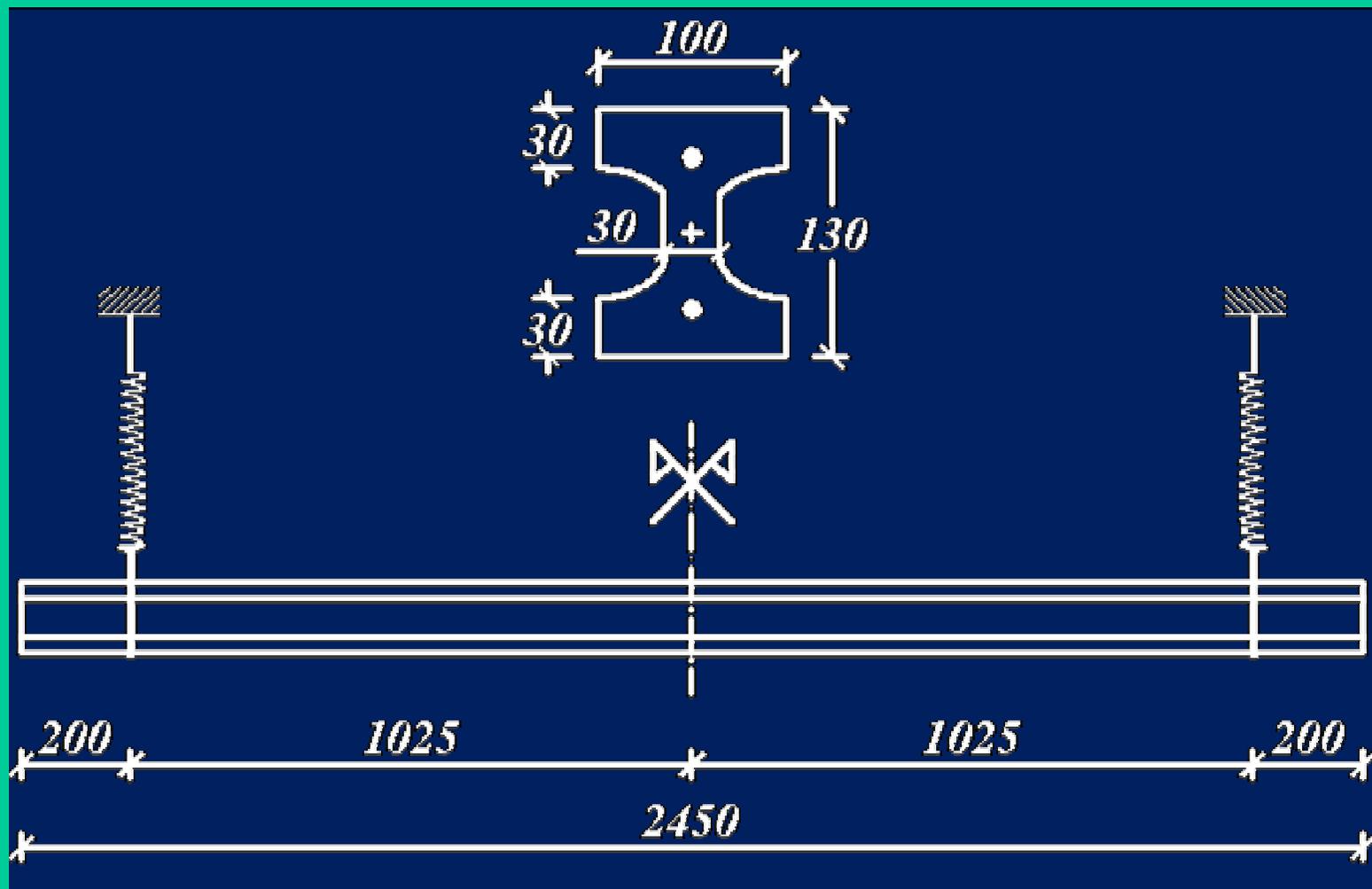
The dynamic measures were obtained using an impact hammer and working in a 0 and 800 Hz range of frequencies with a resolution of 0.5 Hz. The dynamic measures of frequencies $f_1$, $f_2$, $f_3$ and $f_4$ were recorded **for B2 beam** from the beginning of the corrosion process.

The experimental values confirm that in PRC beams the variation of frequencies is not significant during the initial corrosion process.

# Analysis by FEM

## Beam free-free ends



Modo1   94.67Hz

Modo2   254.14Hz

Modo3 479.36Hz

Modo4   754.81Hz
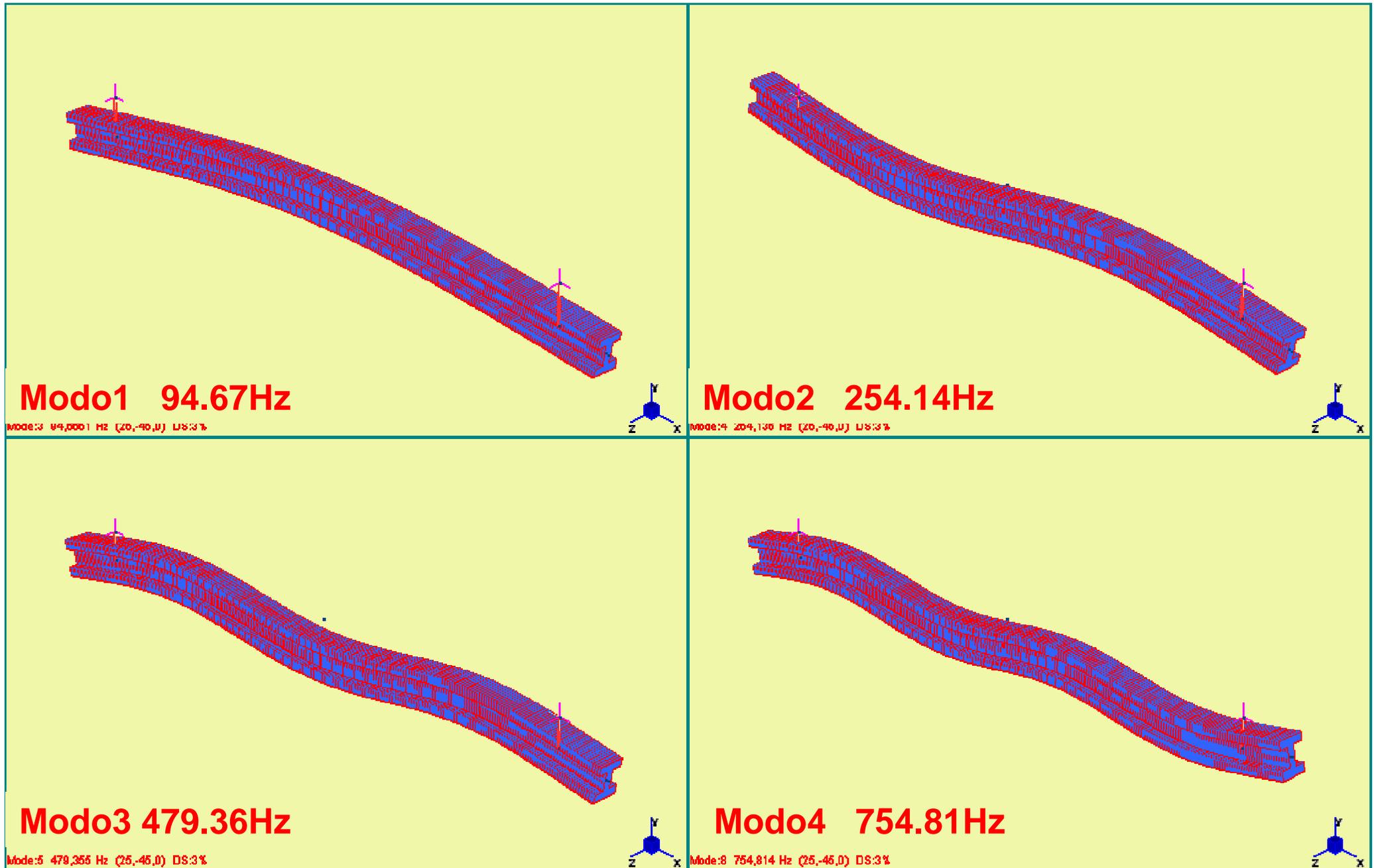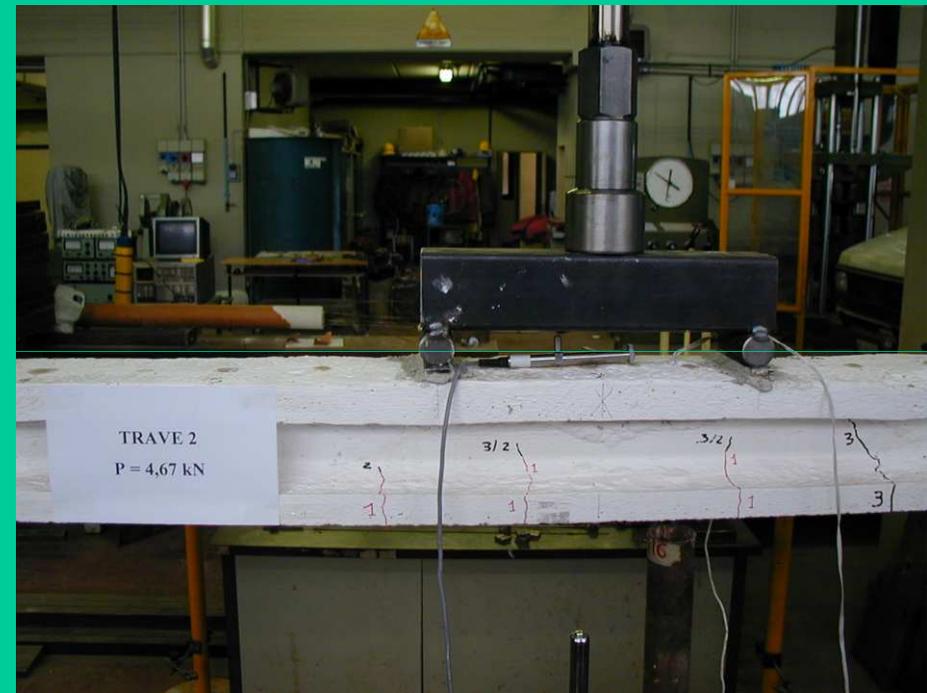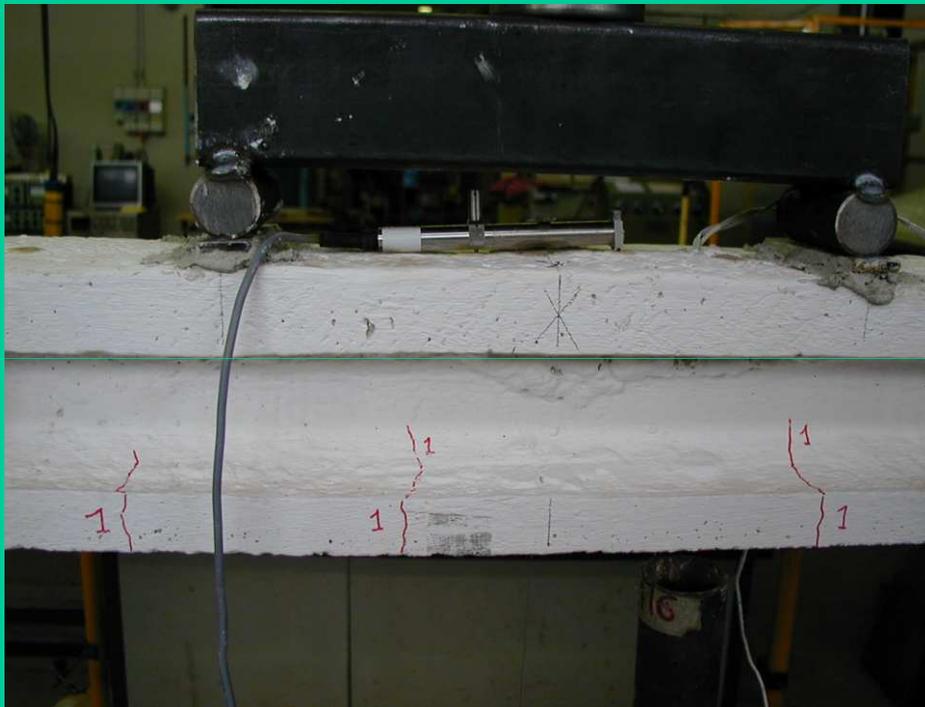
The experimental frequency values obtained by the dynamic tests show a relationship between the corrosion damage in B2 and changes in the frequencies. Although evident phenomena of damage such as cracks on the compressive concrete's surface were not present, the PRC beam, B2, subjected to artificial corrosion process, suffered from a reduction of frequency values greater than the values recorded in beam B1.

**Experimental frequency values during the corrosion process (beam B2).**
**\* Days after construction of beam**

| Days* | $f_1$ (Hz) | $\Delta f_1/f_1$ (%) | $f_2$ (Hz) | $\Delta f_2/f_2$ (%) | $f_3$ (Hz) | $\Delta f_3/f_3$ (%) | $f_4$ (Hz) | $\Delta f_4/f_4$ (%) |
|---|---|---|---|---|---|---|---|---|
| t=0 | 93.628 | - | 249.870 | - | 461,107 | - | 706.271 | - |
| 42 | 94.174 | -0.583 | 249.520 | 0.140 | 459.556 | 0.336 | 706.975 | 0.100 |
| 56 | 93.870 | -0.258 | 248.803 | 0.427 | 457.838 | 0.709 | 705.046 | -0.173 |
| 111 | 94.330 | -1.407 | 248.978 | 0.173 | 459.150 | -1.108 | 705.638 | -0.015 |
| 128 | 93.628 | 0,000 | 247.170 | 1.080 | 453.600 | 0.327 | 701.860 | 0.624 |

**Experimental data measured by static and dynamic tests data for B2 and B1 beams.**
**\*Beam damaged by corrosion process**

| Beam | Degree | Load (kN) | Mmax/Mu,th (%) | curvature $(1/mm)^{-6}$ | $\delta$ (mm) | $f_1$ (Hz) | $f_2$ (Hz) | $f_3$ (Hz) |
|---|---|---|---|---|---|---|---|---|
| B2* | $D_0$ | 0.00 | 0.00 | 0.00 | 0,00 | 95.622 | 251.41 | 464.48 |
| | $D_1$ | 2.47 | 33.71 | 2.3 | 1.2 | 94.426 | 248.96 | 460.77 |
| | $D_2$ | 3.73 | 50.84 | 13.3 | 3.8 | 91.824 | 247.36 | 454.27 |
| | $D_3$ | 4.03 | 54.78 | 16.3 | 6.8 | 90464 | 244.02 | 452.05 |
| B1 | $D_0$ | 0.00 | 0.00 | 0.00 | 0.00 | 96.931 | 255.99 | 476.34 |
| | $D_1$ | 2.47 | 33.71 | 2.3 | 1.1 | 96.616 | 255.83 | 475.70 |
| | $D_2$ | 3.73 | 50.84 | 6.9 | 2.6 | 94.164 | 254.11 | 469.91 |
| | $D_3$ | 4.67 | 63.48 | 10 | 6.2 | 92.468 | 251.48 | 466.97 |

# Beam B2, subjected to artificial corrosion process, suffered from a reduction of frequency values greater than the values recorded in beam B1.
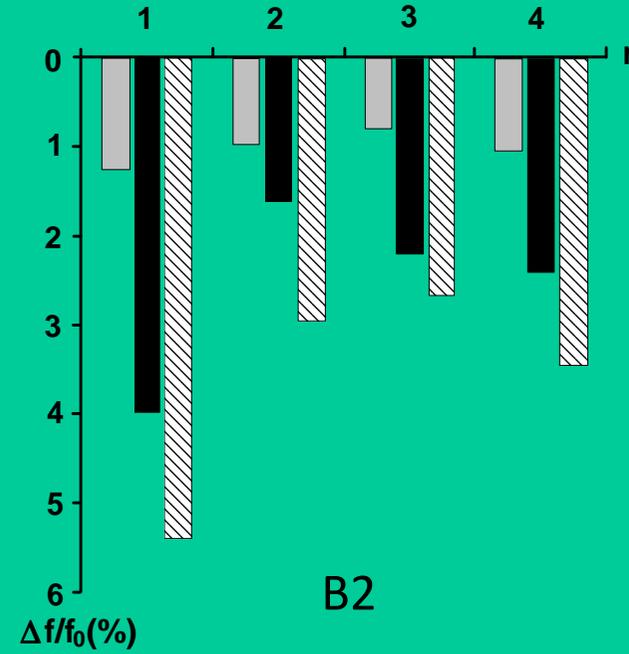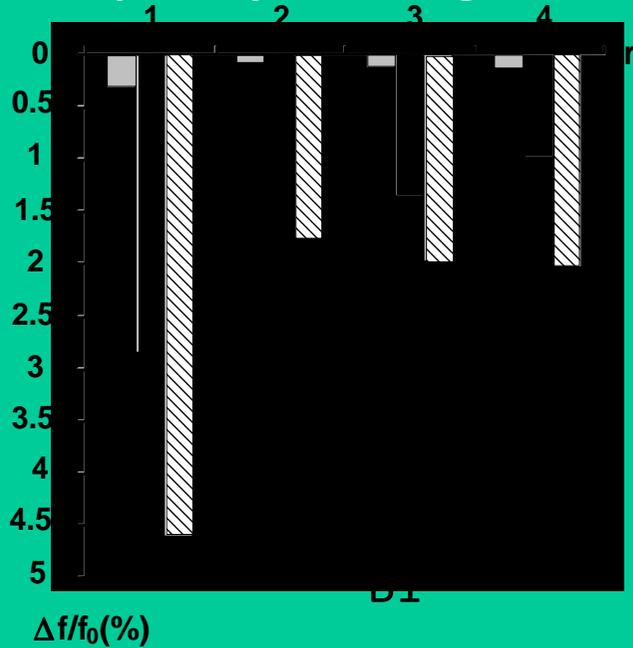


Frequency variation values at the different degree of damage (D1-D2-D3) for different modes of vibration
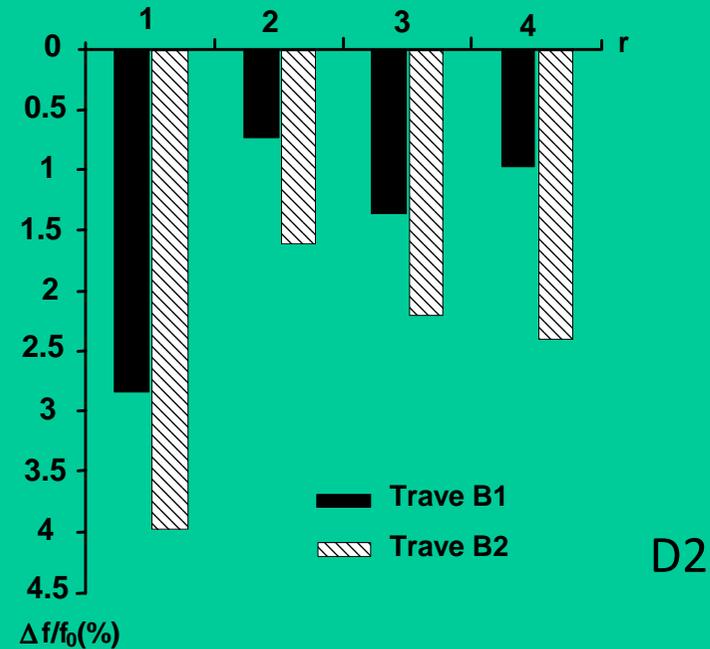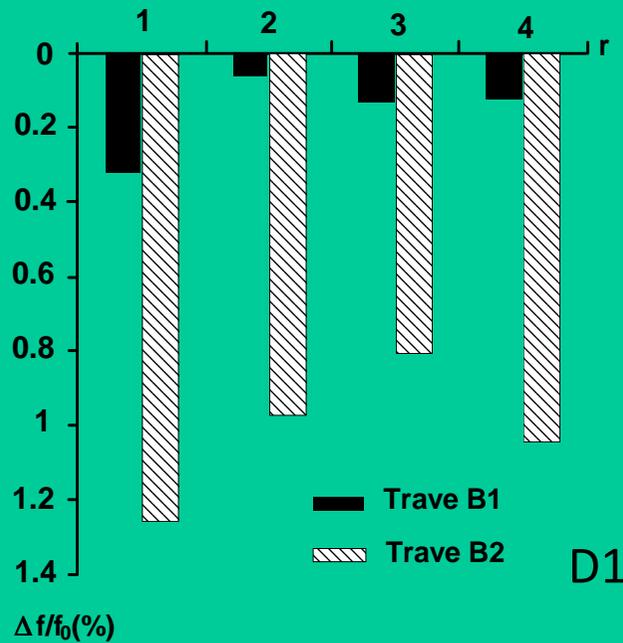
The main effects due to the corrosion process on the reinforcement located in the compressive zone of pre-stressed beam B2, is a loss of stiffness in the experimental moment-curvature diagrams.
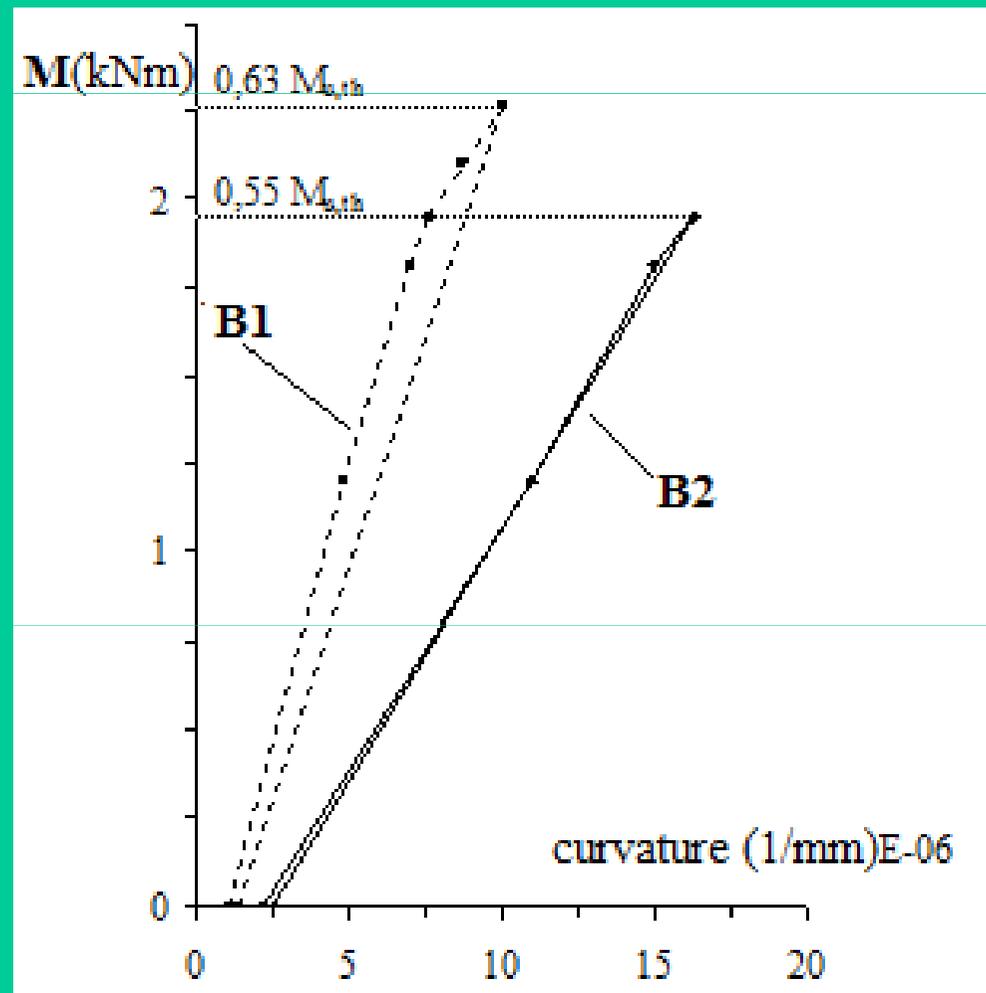
# Conclusions

The PRC/RC beams subjected to corrosion of the reinforcement present widespread cracks on the concrete.
The static and dynamic responses of beams are influenced by damage due to corrosion.
Investigations carried out on PRC/RC beams have shown that the response is mainly linked to the softening of compressive concrete damaged by tensile stress due to corrosion of steel bars.

By experimental tests following conclusions may be summarised:

1. Damaged beams by corrosion present a decrease of stiffness in the elastic field with values of coefficient of damage normally higher than 20%;

2. Reduction of frequency values have been measured in PRC/RC beams;

3. An increase of frequency variation have been measured in PRC/RC beams damaged by corrosion.

# THANK YOU FOR YOUR ATTENTION

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