# STATISTICAL DATA COMBINED WITH LINEAR AND NON-LINEAR ANALYSIS TO INTERPRET BRIDGE LOAD TESTS

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## SUMMARY

Load tests provide valuable information about the actual behaviour of bridges. As such, they offer one of the best methods to reveal the abnormal behaviour of a bridge. The large number of load tests carried out by IBAP over the last two decades allowed a comparative and statistical study, leading to a better understanding of the behaviour of different families of bridges.

While the deflections under loading can be precisely measured, their prediction remains difficult. Combining the statistical results with a finite element analysis leads to more accurate predictions of deflections under loading. The modulus of elasticity of concrete for each of the twenty bridges analysed was measured in situ by the ultrasonic pulse method. In addition, thirteen bridges were cored. The influence of the level of load balancing, of the loading level and of the reinforcement on the effective stiffness of a bridge is discussed.

A non-linear analysis of a partially post-tensioned bridge shows the influence of the modulus of elasticity of concrete, the tensile strength of concrete, the load balancing level and loading level on the concordance and the affinity between measured and calculated deflections.

## 1. INTRODUCTION

Load tests allow to determine and quantify the global behaviour of bridges under substantial loading. The Swiss Codes recommend a load test for any new bridge with spans exceeding 20 m. Thus, the majority of load tests performed in Switzerland are acceptance tests, aimed at examining the serviceability of a new bridge before it is put into service. The acceptation of a bridge is generally based on the concordance between the measured and calculated deflections, on residual deformations, on cracking and on the affinity between measured and calculated deflected shapes. A strong correlation between an unsatisfactory short-term behaviour and an abnormal long-term behaviour, characterised by a non-stabilisation of cracking and sagging has been observed. An unsatisfactory behaviour during a load test is an alarm signal, leading to more frequent inspections and early maintenance work.

The Institute of Reinforced and Prestressed Concrete (IBAP) of the Swiss Federal Institute of Technology (EPFL) has been involved with over 200 full-scale bridge load tests over the past 20 years. The bridges are located mainly in the French speaking part of Switzerland.

The main results of the static and dynamic load tests performed on these two hundred bridges, along with information on their geometry, have been collected in a computerised database. Table 1 shows the structural system and type of cross-section of all bridges contained in the database. A large majority of the tested bridges (178) are post-tensioned concrete structures.

Statistical analyses of the database have been carried out and some general conclusions on the actual behaviour of a bridge under loading have already been collected and published.

## 2. STATISTICAL ANALYSIS

The influence on the deformations of the non-structural elements, usually neglected in the calculation, was investigated. It was found that such elements as parapets, asphalt layer and reinforcement have an important influence on the deformations. It should be noted that the effect of non-structural elements is normally neglected for the calculation of deflections.

In order to deal with a homogeneous set of results, the statistical analysis focused on intermediate spans of post-tensioned bridges with the structural system being a continuous beam with a minimum of three spans. This resulted in 88 bridges. Filtration and comparison of data showed that bridges tested with reinforced concrete parapets have systematically a smaller ratio of measured to calculated deflections. It means that they are stiffer than bridges tested without parapets. Similarly, bridges tested with an asphalt layer are systematically stiffer than bridges tested without an asphalt layer.

An analytical deterministic approach was used to determine the influence of the non-structural elements. The inertia of each one of the 88 bridges was calculated, taking into account the actual inertia of the asphalt layer, of the parapets and of the reinforcement including post-tensioning.

The effective inertia of the asphalt layer was taken as a function of its temperature during the load test. The effective inertia of parapets was taken according to the type of parapets and their connection with the superstructure.

Because of micro-cracking induced by shrinkage, creep and thermal stresses, the parapets are actually less stiff than the normal concrete of the bridge. For this reason, a corrective factor called the “effectiveness” of the parapets is introduced. It was found that an effectiveness of 75 % gives the best results. Fig. 1 shows a cross-section of a bridge with the non-structural elements to be taken into account to obtain the effective inertia of the superstructure.

The asphalt layer was considered as a part of the superstructure with a modulus of elasticity depending on the ambient temperature. Figure 2 shows the modulus of the asphalt layer as it was taken into account in the deterministic analysis.

This modulus of elasticity, based on laboratory tests found in the literature, was used in the deterministic approach and gave results of good concordance with the statistical results. Considering the ambient temperature equal to the asphalt temperature is an acceptable approximation in most cases of our load tests, because they are generally carried out in the early morning and in a covered weather. In the rare cases, when the temperature is higher than 20 °C, the influence of asphalt layer is very small and can be neglected.

The deterministic results confirmed the statistical results. Table 2 shows a comparison between the participation to the effective inertia of non-structural elements as obtained by the statistical and deterministic approaches.

## 3. MODULUS OF ELASTICITY OF CONCRETE

To obtain reliable calculated deflections, the modulus of elasticity should be precisely determined. Code formulae for estimating the modulus of elasticity of concrete based on concrete strength are inaccurate (Baalbaki et al, 1992). The modulus of elasticity is strongly influenced by local parameters such as the aggregates (Giaccio et al, 1992), the composition of the cement paste and the cure of the concrete. The problem is even more complex, as the modulus of elasticity is time- and strain-dependent.

A large campaign of measurements was organised by IBAP to investigate the modulus of elasticity of existing bridges. Thirteen bridges have been cored and ultrasonic measurements have been performed on twenty bridges. For two bridges recently constructed, a large number of moulded cylinder samples taken during the construction were tested at various ages in laboratory, along with ultrasonic measurements and the drilling of cores. The first results show that the moulded cylinder samples taken during construction are a valid method to determine the modulus of elasticity.

The ultrasonic measurements offer an interesting alternative for the determination of the modulus of elasticity of concrete in an existing structure. Special care should be taken of the measurement technique. The modulus of elasticity was measured by both ultrasonic measurements and drilled cores at the same time for 10 bridges. The ultrasonic measurements were carried out using the direct method. A set of 3 cores, of diameter $\phi = 100mm$ and length ●$= 200mm$, were drilled from each bridge. The comparison of results obtained by both methods shows that the modulus of elasticity obtained by direct ultrasonic measurements is close to the modulus obtained on drilled cores. The average ratio of the modulus of elasticity measured by ultrasonic measurements to the modulus of elasticity measured on drilled cores is $\frac{E_c\,(\text{ultrasonic measurements})}{E_c\;(\text{drilled cores})} = 1.02$ and the standard deviation is $\sigma = 0.066$.

## 4. LINEAR ANALYSIS

Linear analysis is usually used to predict deflections under a load test. This approach assumes that the concrete is a homogeneous material, that the stress-strain relationship is linear and that the concrete remains uncracked. Most Swiss bridges are partially prestressed and can be cracked under substantial loads, as they occur in load tests. Even if cracks are not always observed during the load test, a loss of rigidity was observed in some bridges. The loss of rigidity was typically observed in the case of bridges highly loaded and/or slightly post-tensioned.

As a first step, a linear analysis was used to study a group of twenty post-tensioned continuous bridges. The bridges were chosen to represent typical highway bridges. Most bridges are box-girders of constant depth, and the others are of open cross-sections with two girders. The bridges are in a straight line or very slightly curved with an average deck width of 13 m.

The bridges were analysed taking into account the inertia of the structural cross-section together with the non-structural elements as parapets, asphalt layer and reinforcement including post-tensioning.

### 4.1. Influence of Balancing Level on Bridge Rigidity

Fig. 3 shows the correlation between the balancing level of post-tensioning and the apparent modulus of elasticity, defined as the modulus required for calculated deflections equal to measured deflections at mid loaded span. The apparent modulus of elasticity is an imaginary modulus which represents the elasticity of concrete together with the reduction of rigidity of the superstructure by cracking due to insufficient post-tensioning. It can be expressed as in equation 1.

$$E_{\text{apparent}} = \frac{E_{\text{concrete}} \times I_{\text{effective}}}{I_{\text{homogeneous section}}} \qquad \text{(Eq. 1)}$$

The balancing level is the ratio of permanent loads balanced by the parabolic post-tensioning cables. It appears that bridges with low balancing levels present a lower apparent modulus of elasticity than bridges with a high levels of load balancing. Because the modulus of elasticity measured on drilled cores or by ultrasonic measurements do not show a significant correlation with the apparent modulus, we can conclude that the apparent modulus of elasticity mainly expresses the reduction of rigidity.

The balancing level as it is usually defined does not account for straight cables. Only five bridges of the studied group have straight cables. They were constructed by the incremental launching method. As it is shown in Fig. 3, the bridges constructed by the incremental launching method have lower rigidities. This reduction of rigidity can be explained by cracks occurring during the construction. Thus the concrete is pre-cracked and the participation of concrete in tension to the rigidity is largely reduced. In spite of the reduction of rigidity of bridges constructed by the incremental launching method, their rigidities remain high compared to bridges constructed on fixed scaffolding, because of their low slenderness. There is usually no problem regarding the absolute value of the deflections in this type of bridges.

**4.2. Influence of Loading Level on Bridge Rigidity**

A significant correlation can be observed between the level of loading used for a load test and the apparent modulus of elasticity of the concrete (see eq. 1). The level of loading is defined as the ratio of the moment induced by the test load to the moment induced by the code design loads. For simplification, the moments are calculated at mid-span of the loaded span, considered as a simple beam. In figure 4, bridges loaded heavily during the load test exhibit a lower apparent modulus of elasticity.

As can be seen by comparing figures 3 and 4, the bridges that exhibited a lower stiffness were also bridges that had a lower level of balancing. In most studied bridges, the moments at mid-span or at the support do not induce tensile stresses exceeding the tensile strength of concrete indicated in the codes. Only 4 bridges have a maximum tensile stress exceeding 2 $N/mm^2$. The bridges built by the incremental launching method were relatively highly loaded during the load test. This can explain the lower observed rigidity. Other possible causes are the low level of load balancing and the damaging effect of the launching process.

Other factors, difficult to quantify, can influence the rigidity of bridges as the effects of temperature, excessive temporary loads, creep and shrinkage. They provoke cracks or micro-cracks which reduce the bridge rigidity.

Only a small variation of the modulus of elasticity of concrete has been observed among the bridges under investigation (from 34 to 42 GPa for 13 cored bridges). This variation is much smaller than that of the apparent modulus of elasticity (from 26 to 46 GPa). All bridges in the studied group are located in a relatively small geographical region.

The linear analysis of this group of bridges shows the influence of load balancing and loading levels on the global rigidity through their influence on the deformations at mid-loaded span. This analysis does not always lead to a good affinity between the measured and calculated deflections for the loaded and adjacent spans. Stress calculations showed that some bridges have tensile stresses locally exceeding the tensile strength of concrete, which is likely to cause cracking. In the case of cracked bridges, a non-linear analysis should be used as the case of the Talent bridge clearly demonstrates in the following section.

## 5. DEFORMATIONS IN PARTIALLY POST-TENSIONED BRIDGES

The inclusion of the non-structural elements in the inertia and the measurement of the modulus of elasticity of concrete are essential to obtain a reliable calculation of deflections. The deflections are normally calculated using a linear analysis, considering the concrete as a homogeneous elastic material. However, the effective inertia of partially post-tensioned bridges depends on the loading and load balancing levels. This effect can only be accounted for a non-linear analysis.

The case of the “Talent” bridge aims to show the influence of cracking in the superstructure on the deflections under short term loading. This analysis has been performed using the moment-curvature relationship developed by IBAP and adopted in the CEB-FIP Model Code (1990). This relationship has been implemented in the program MAPSDIFF developed in collaboration by MAPS Diffusion S.A. and IBAP. The Talent bridge is located on the highway Lausanne-Yverdon. The bridge was built and tested in 1981. The bridge consists of 8 spans as follows: 38.0 m, 6 x 49.3 m and 40.4 m, for a total length of 374 m. The cross-section is a box-girder of 2.50 m depth and 12.46 m width with a reinforced concrete parapet on either side. The bridge is post-tensioned and 64 % of dead load is balanced by the post-tensioning cables. During the load test, the bridge was loaded by 12 lorries of 250 kN. The load level during the load test was 1.26 which is higher than the usual load levels (ideally from 0.8 to 1.0). Under the first loading a cracking sound was heard. A careful inspection, just after unloading, did not detect any cracks. However, after several years of service, cracks appeared at the supports and at mid span and can be visually observed without live loads. The analytical study presented here will focus on a symmetrical loading case on the second span of the Talent bridge.

### 5.1. Linear Analysis

The deflections under loading were measured by IBAP, and calculated by the designer using a modulus of elasticity of concrete of 39 GPa. Figure 5 shows the measured deflections together with the calculated deflections.

Figure 9 shows a good concordance between measured and calculated deflections at mid loaded span. However, the affinity between the two deflected shapes is not satisfactory. The ratio of measured to calculated deflections is about 20 % lower in the adjacent span than in the loaded span. An elastic analysis showed that tensile stresses at mid loaded span reach 4.2 N/mm$^2$ under the test loads and the permanent loads. Because the tensile stresses under loading are higher than the tensile strength of concrete, a non-linear analysis was performed.

### 5.2. Non-Linear Analysis

The tensile strength of concrete is the most important parameter influencing the deflections calculated taking cracking into account. In the studied case, as shown in figure 6, the deflection at mid loaded span increase from 17.5 mm to 24 mm (37 %) if the tensile strength changes from 3 N/mm$^2$ to 1 N/mm$^2$. Figure 6, obtained for a modulus of elasticity of concrete of 40 GPa, shows that the tensile strength should be 2.7 N/mm$^2$ to have a calculated deflection equal to the deflection measured at mid loaded span. This value is very close to the tensile strength of concrete of 2.5 N/mm$^2$ indicated in the Swiss codes for this type of concrete.

Using a tensile strength of concrete of 2.5 N/mm$^2$ and varying the modulus of elasticity from 35 GPa to 48 GPa, the deflections at mid-loaded and adjacent spans were calculated and are presented in Fig. 7. An increase of the modulus of elasticity of 25 % from 35 GPa to 44 GPa decreases the deflection at mid-loaded span by 19 %. This means that deflections in cracked bridges are less sensitive to the modulus of elasticity than the uncracked bridges, because of the decrease of working concrete. The analysis indicates that a modulus of elasticity of concrete of 42 GPa would make the calculated deflections equal to the measured deflections.

The modulus of elasticity of concrete was measured on drilled cores and by ultrasonic measurements. The average modulus of elasticity of three drilled cores is 41.6 GPa. Values ranging from 40 to 47 GPa were obtained using the ultrasonic measurements.

Based on the measurement of the modulus of elasticity and the previous parameteric analysis, a non-linear analysis was performed using a modulus of elasticity of concrete of 42 GPa and a tensile strength of concrete of 2.5 N/mm$^2$. The parapets, asphalt layer and reinforcement were taken into account in the stiffness as indicated in section 2. Fig. 8 shows the resulting calculated deflections together with the measured deflections. It can be observed that both curves are nearly identical, both in the loaded and in the adjacent span.

The non-linear analysis allows to describe the actual behaviour of the bridge and to obtain predicted deflections matching closely the measured deflections. The non-linear analysis also improves the affinity between the measured and calculated deflected shapes, as Fig. 9 clearly illustrates.

### <u>5.3. Influence of Loading and Post-tensioning Levels on Rigidity</u>

When the tensile stresses exceed the tensile strength of concrete, cracks appear and the stiffness of the bridge decreases. The global stiffness of a cracked structure depends on the level of loading and post-tensioning. In order to quantify the influence of the load balancing level, the deflections of the Talent bridge were calculated at mid loaded spans for three balancing levels: existing post-tensioning force, 90 % of the existing post-tensioning force and 110 % of the existing post-tensioning force. For each of the levels, the deflections were calculated for several load levels between the level at which first cracking occurs and the load level 1.26 used during the load test. Fig. 10 shows the ratio of the deflections at mid-span obtained without cracking ($w_1$) to the deflections obtained with cracking ($w_2$). It can be easily observed that an increase in the load balancing level rigidifies the bridge considerably and prevents cracking. With an increase of 10 % of the post-tensioning force, cracking is avoided until a load level equal to 1.0 (only occasionally exceeded during the service life). However with a decrease of 10 % of the post-tensioning force, the bridge is cracked for a load level of 0.5 (load level of every day) and its stiffness is reduced accordingly. For a load level of 1.26, an increase of 10 % of the post-tensioning force decreases the deflections by 23 %.

## 6. CONCLUSIONS

A strong correlation between an unsatisfactory behaviour during a load test and an abnormal long-term behaviour of a bridge has been observed. The abnormal long-term behaviour is usually characterised by a non-stabilisation of cracking and sagging.

The contribution to the rigidity of the parapets, the asphalt layer and the reinforcement should be taken into account for an accurate calculation of deflections. The modulus of elasticity should be determined experimentally (preferably by taking concrete samples during construction), as the formulae relating the modulus of elasticity of concrete to the compressive strength are inaccurate.

The global rigidity of bridges, even if they are theoretically not cracked, depends on the balancing and loading levels. An important reduction of rigidity has been observed in insufficiently post-tensioned and/or heavily loaded bridges. Thermal stresses, excessive temporary loads, creep and shrinkage can provoke cracks or micro-cracks which also reduce the bridge rigidity. Bridges constructed by the incremental launching method have a lower rigidity than bridges constructed on fixed scaffolding. However, this reduction caused by cracking or micro-cracking during the launching process does not lead to excessive deflections because these bridges are generally very rigid.

When bending tensile stresses exceed the tensile strength of concrete, a non-linear analysis should be performed. Such an analysis improves the concordance between the measured and calculated deflections and the affinity between the two deflected shapes.

In the case of Talent bridge, a non-linear analysis allowed to understand and describe the actual behaviour of the bridge. It enabled to explain and quantify the increase of deflections due to cracking. It was shown that an increase of prestressing level rigidifies the bridge considerably and prevents cracking under usual loads. Thus, considering the long-term behaviour, bridges should be preferably designed with a post-tensioning level able to prevent cracking under usual loads.

## 7. REFERENCES


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| Structural system | | Cross-section | |
|---|---|---|---|
| Type | Number | Type | Number |
| beam | 179 | box-girder of const. depth | 58 |
| rigid portal frame | 21 | box-girder of var. depth | 25 |
| arch | 5 | slab beam | 32 |
| cable stayed | 5 | open section | 95 |
| Total | 210 | Total | 210 |

Table 1: Structural system and type of cross-section of all bridges contained in the database

| Element | Participation to inertia | |
|---|---|---|
| | statistical approach | deterministic approach |
| Asphalt layer | 6 % | 4.7 % |
| R.C. parapets | 24 % | 28 % |
| Reinforcement | - | 5 % |

Table 2: Comparison between the participation to inertia of non-structural elements based on the statistical and deterministic approaches

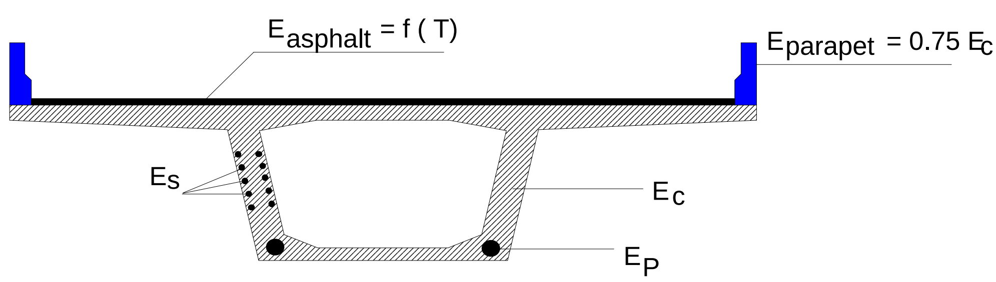


Figure 1: Cross-section with the non-structural elements

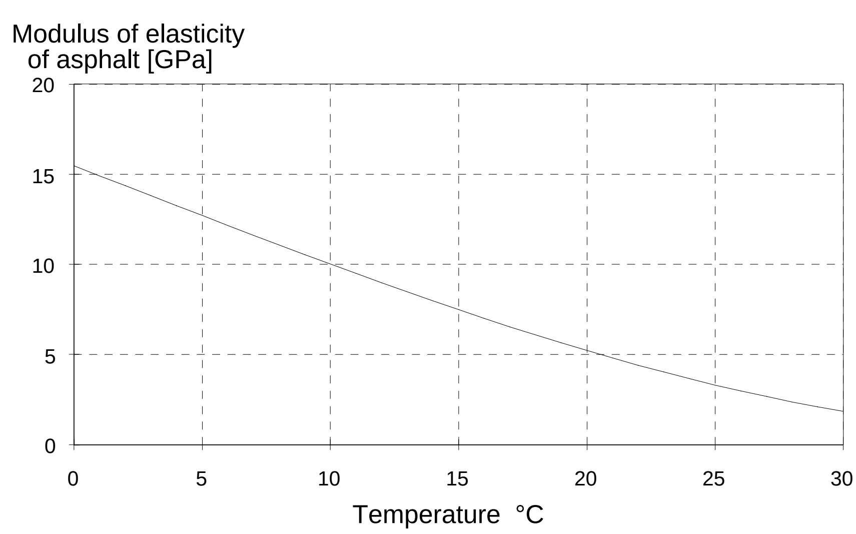


Figure 2: Modulus of elasticity of asphalt layer as a function of temperature

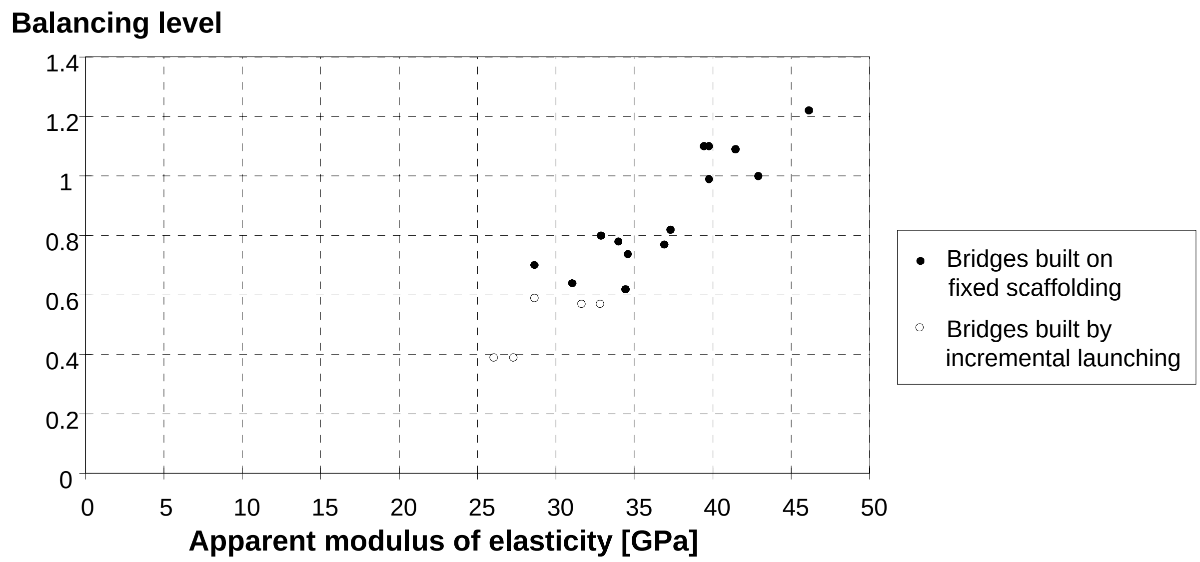


Figure 3: Apparent modulus of elasticity versus balancing level

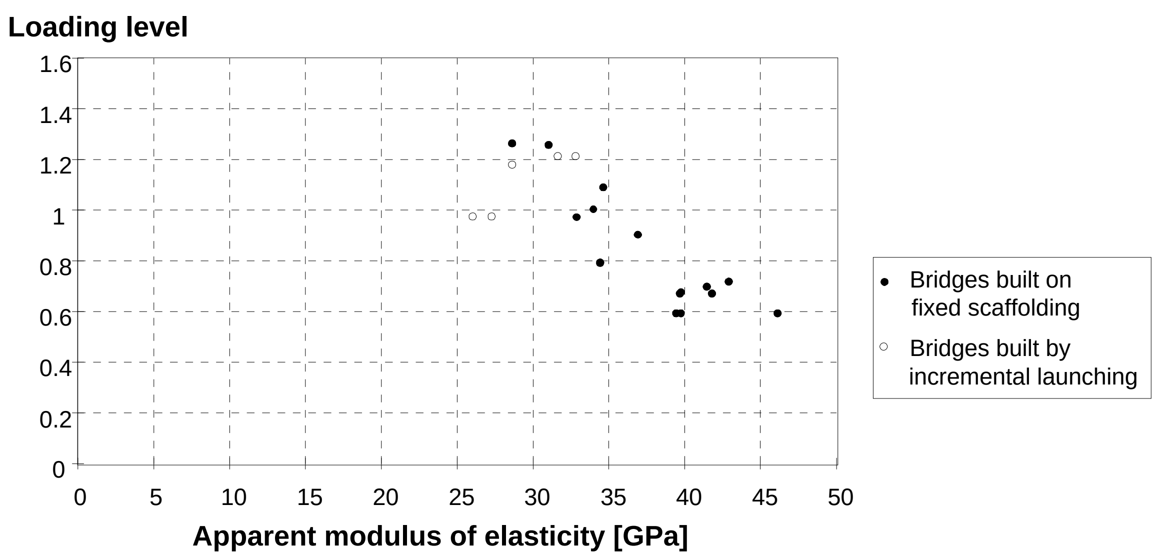


Figure 4: Apparent modulus of elasticity versus loading level

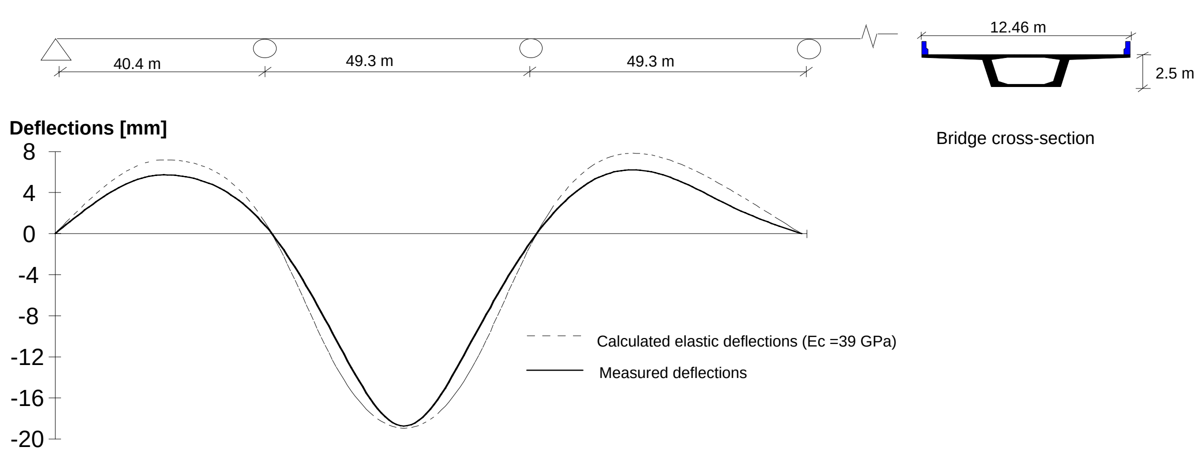


Figure 5: Measured deflections compared to calculated elastic deflections

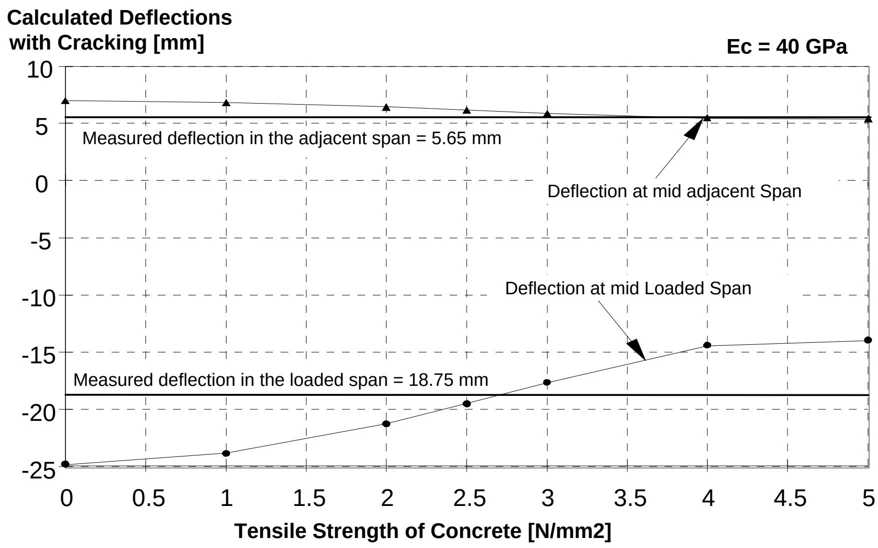


Figure 6: Calculated deflections at mid loaded and adjacent spans as a function of the tensile strength of concrete

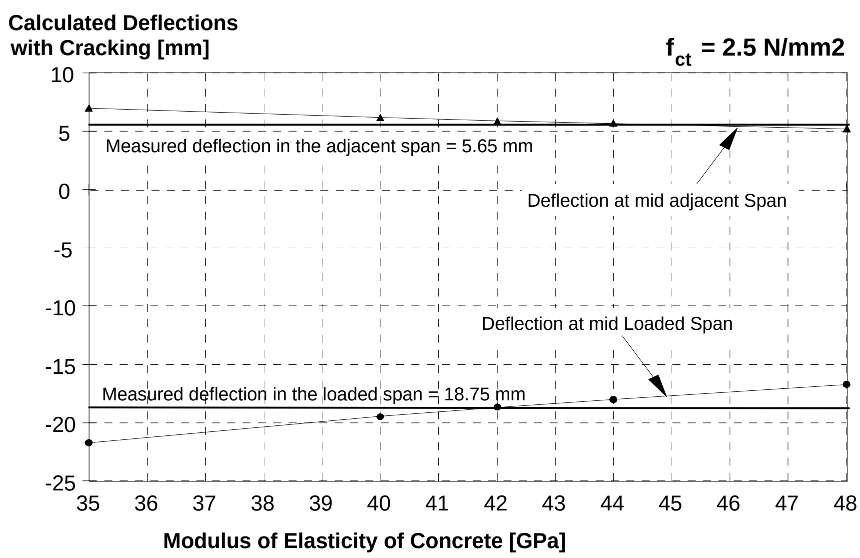


Figure 7: Calculated deflections at mid loaded and adjacent spans as a function of the modulus of elasticity of concrete

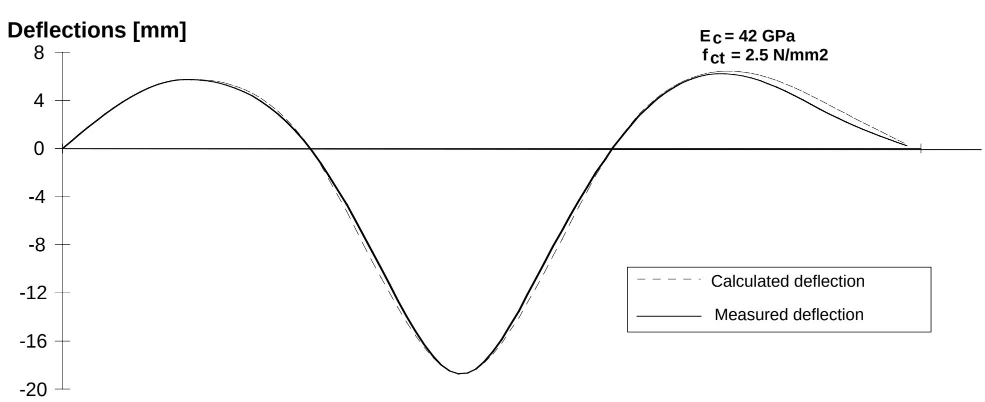


Figure 8: Calculated deflections resulting from the non-linear analysis compared to measured deflections

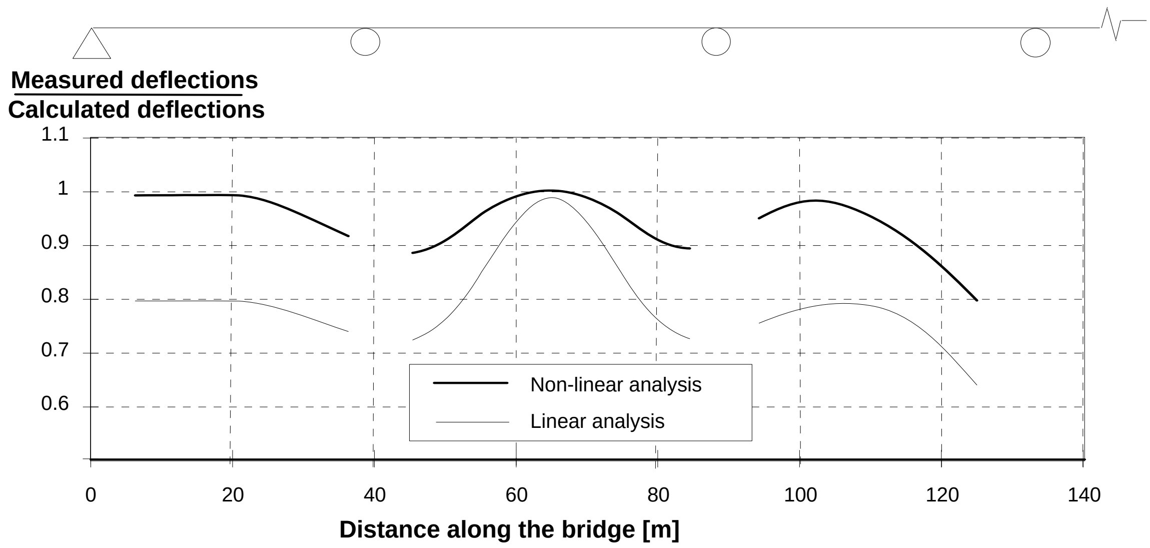


Figure 9: Ratio of measured deflections to calculated deflections obtained by linear and non-linear analysis in the loaded and adjacent spans

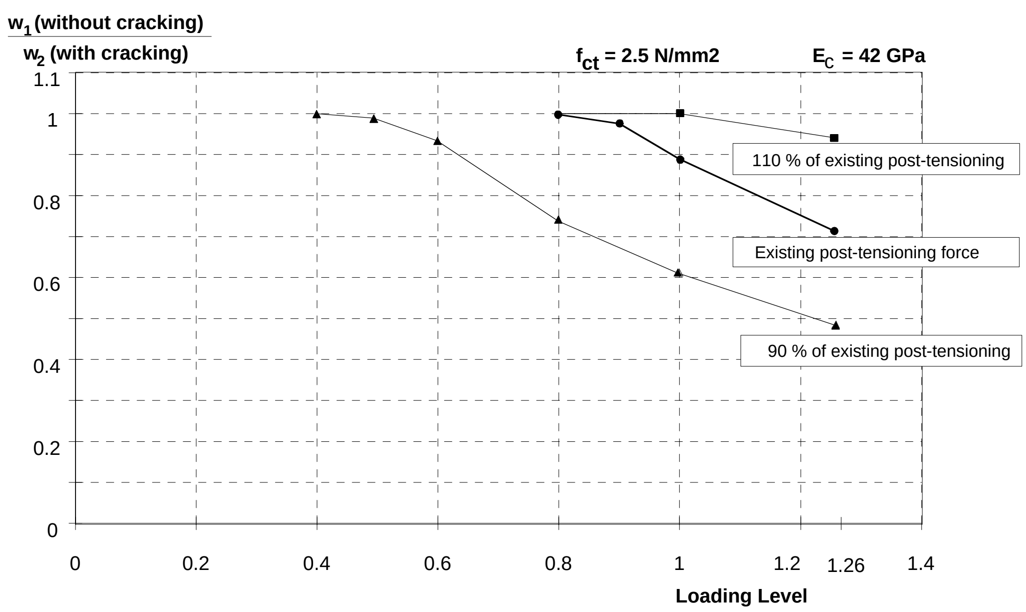


Figure 10: Ratio of the deflections obtained without cracking to the deflections obtained with cracking as a function of the load and post-tensioning levels