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Review of the limiting tensile strain method for predicting settlement induced building damage

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ABSTRACT: To predict settlement damage on adjacent buildings due to excavation induced ground movements, the limiting tensile strain (LTS) method is currently used in the design stage of projects in urban surrounding. In order to make the method applicable in practice engineering, the developers of this method have supposed some basic assumptions. This paper presents the results of a fundamental analyses of these assumptions from structural point of view and its impact on the calculated tensile strains in the buildings. Suggestions are made for an improved use of the method.

1 INTRODUCTION

Excavation induced ground movements can cause damage on adjacent structures. The limiting tensile strain (LTS) method is currently used in engineering practice to predict the degree of possible settlement damage on the buildings. This method assumes the fully transfer of differential ground movements to the adjacent building, neglecting soil-structure interaction effects. In order to make the method applicable in practice engineering, the developers of this method have chosen some basic assumptions. This paper presents the results of a fundamental analyses of these assumptions from structural point of view and its impact on the calculated tensile strains in the buildings. Suggestions are made for an improved use of the method. It should be mentioned that the important influence of soil-structure interaction on the damage prediction is not scope of this paper and is under research of the author at this moment.

2 GENERAL

2.1 *Principles of the limiting tensile strain method (LTS)*

The LTS-method is an empirical, analytical method to predict settlement induced building damage. The structural section of a building is modeled as a weightless, rectangular, isotropic elastic beam of the length L , the height H and the material parameter E/G . The imposed (horizontal and vertical) ground deformations on foundation level, caused by an external source (tunnelling, excavation etc.), are assumed to be fully transferred to the building regardless soil-structure interaction effects. The fully transfer

of the (differential) green field ground movements implies the building to be forced to follow the pre-described differential settlements, causing the largest distortion of the building, thus the highest strain values. The method is therefore considered to provide a conservative estimate for the expected damage. Difference in the damage prediction is made between the sagging and the hogging zone. The imposed tensile strains in the structure are calculated with analytical beam equations for a simply supported beam (taking into account shear deformations), which is loaded with a fictive point load causing the ground deflection profile.

The calculated diagonal and bending strains in the beam are consequently compared to different limiting tensile strain values representing different damage classes with an indication of degrees of damage (defined in terms of the ease of repair, see BRE (1981)). The method is developed by Burland & Wroth (1974) and Boscardin & Cording (1989). **Figure 1** shows the principle of the method for a building in the sagging zone. It should be noted that the above mentioned authors have chosen a fictive central point load to fit the deflection profile.

2.2 *Basic assumptions in the LTS*

The following basic assumptions in the principle of the method are discussed in this paper:

- Review of the correct use of the Timoshenko beam equations for the determination of the strains in the structure according to the currently used LTS-approach.
- For long buildings, only the part of the building which is situated inside the 1 mm settlement

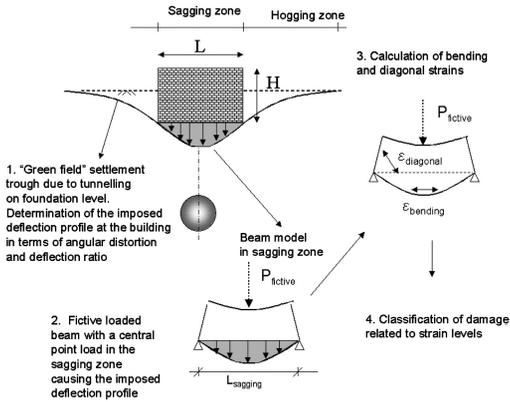


Figure 1. Principle of the limiting tensile strain method for the influence of vertical differential settlements.

influence line is currently considered for the calculation of the maximum tensile strains. Can the part of the building extending beyond the theoretical 1 mm line be neglected in the calculation of the maximum tensile strains?

- Choice of the damage criteria different approaches of different authors causes different results. The angular distortion (suggested in Boscardin & Cording (1989)) or the deflection ratio (suggested Burland & Wroth (1974)) is used. An analyses of the influence of these parameters is presented.

3 TIMOSHENKO BEAM-EQUATIONS

To calculate the tensile strains in the structure the equations presented by Timoshenko & Gere (1972) are used. These equations calculate the overall beam deflection of a beam with a fictive point load P taking into account shear and bending deformations. The contribution of the shear deflection is described with the shear form factor. The current LTS-method uses the equations with a shear form factor of 1.5, based upon the maximum shear strain at the neutral axis of the beam. The actual variation in shear strains over the height of the beam is not taken into account. This leads to an overestimation of the shear deflection contribution and thus to an underestimation of the tensile strains used in the damage prediction according to the tensile strain method.

Timoshenko however also presents solutions derived from the more exact theory of elasticity and the method of virtual work respectively. These equations differ from the equations used in the current LTS approach, because the influence of the shear strain distribution over the height of the beam is properly taken into account when calculating the contributions of the shear deflections to the overall deflection of the beam. For a rectangular beam a shear form factor of

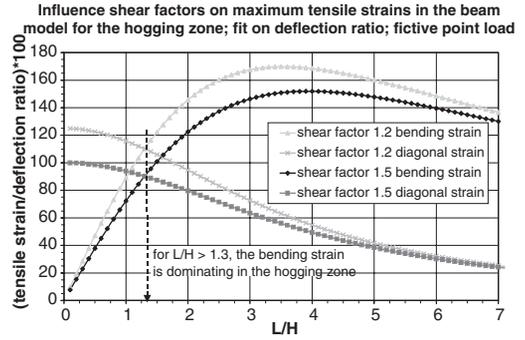


Figure 2. Strains for different shear factors in the hogging zone.

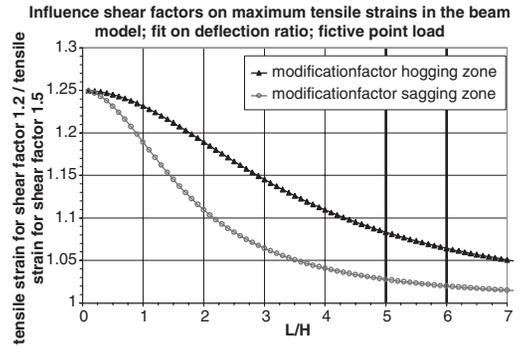


Figure 3. Modificationfactors due to different shear factors.

1.2 is derived by Timoshenko & Gere (1972), instead of the simplified shear factor of 1.5 used currently in the LTS. Using this modified shear form factor, the equations for the deflection ratio due to a fictive point load P in the sagging zone (neutral axis at the mid of the beam) can be written as:

$$\frac{\Delta}{L} = \frac{P \cdot L^2}{48 \cdot EI} + \frac{P \cdot 1.2}{4 \cdot G \cdot A} \quad (1)$$

with E , G and I as building parameters; L is the considered span length of the building; Δ is the maximum deflection of the beam; P is the fictive vertical point load at the midspan of the beam, causing the imposed deflection profile.

The influence of this modification on the calculation of tensile strains for the damage prediction method is analyzed. Figure 2 presents the different strain results for a building in the hogging zone if the different shear factors (1.2 versus 1.5) are used. Figure 3 shows modificationfactors for the maximum tensile strains in the sagging zone and the hogging zone if the shear factor of 1.2 instead of 1.5 is used. The

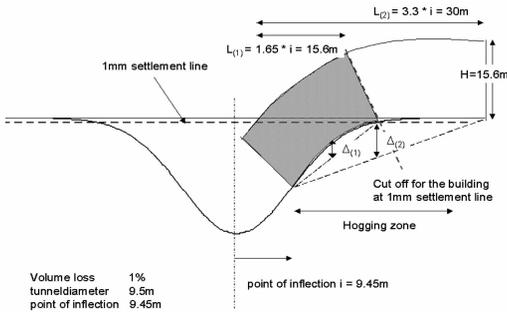


Figure 4. Example for “cutting off” a long structure at the 1 mm line.

correct shear form factor leads to an increase of the strains between 20 and 25% for practical ranges of L/H (between 0.7 and 1.5).

It is therefore recommended to use the above equations with a shear form factor of 1.2 when predicting the building damage using the tensile strain method.

4 LONG STRUCTURE (“CANTILEVER-EFFECT”)

If a building is longer than the influence area of a settlement trough, the current LTS only considers the part of the building inside the influence area for the determination of the strains. The building span length is than limited by the extent of the settlement trough. The 1 mm settlement line is generally used to determine the limit of the influence area of a Gaussian formed settlement trough. The example in figure 4 shows the considered part of the building (see coloured section in figure 4).

The “cantilever” effect of long structures is obviously neglected in the current LTS. The influence of this assumption is analyzed by comparing the calculated strains for the “short” (the “cut off” part of the building inside the 1 mm line) and the “long” structure (the whole building), as shown in figure 4.

4.1 Conclusions cantilever-effect

The cantilever effect for structures, which are extending beyond the 1 mm line can be estimated in terms of the development of the deflection ratio in combination with the change in L/H. For the example of figure 4 it can be concluded that:

- For the considered case the length $L_{(1)}$ of the “short structure” 15.6 m thus the $L_{(1)}/H$ -value is ca. 1. The total length of the “long” structure $L_{(2)}$ is 30 m thus the $L_{(2)}/H$ -value is ca. 2. A comparison of the deflection ratio’s for both cases (the short and the long structure) show an increase of the deflection ratio for the long structure of circa 10%. At the same time

however the L/H-ratio is increasing, which leads to an increase of the bending strains of circa 65% (compared to the short structure; see also figure 2). Combination of these two effects leads to ca. 80% higher bending strains in the considered case, if the long structure is considered.

Thus the “cantilever” effect can cause a significant increase of the strains and has therefore to be considered especially, when the L/H-ratio of a building in the hogging zone is smaller than 3 (which is the case in most situations) and the proceeding length of the structure beyond the 1 mm line is more than one times the length of the structure inside the 1 mm area.

5 ANGULAR DISTORTION OR DEFLECTION RATIO

5.1 Currently used design charts

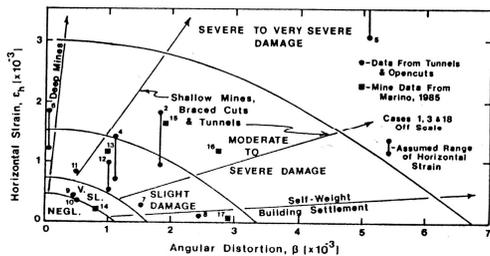
The limiting tensile strain method is developed by different authors and presented in the form of design charts, which are often used in the engineering practice. It should be emphasized that the design charts are only applicable for the case of a massive bearing wall in the hogging zone and the L/H-value of 1 ! Thus for a building with different geometrie (L/Hvalue) and the sagging zone, the use of the design charts do not give correct results. Furthermore the Timoshenko-beam equations used as background of the LTS to derive the design charts given below encounter the assumption of a shear form factor, leading to an underestimation of the strains up to 20% (see chapter 3 of this paper). The considerations presented in the following chapters of this paper include the use of correct shear form factor of 1.2.

The design chart given in figure 5a is presented by Boscardin & Cording (1989). The input parameters are the horizontal strain as a measure for the impact of (differential) horizontal ground movements and the angular distortion as a measure for the vertical (differential) settlements. The design chart derived by Burland et al. (2001) is shown in figure 5b.

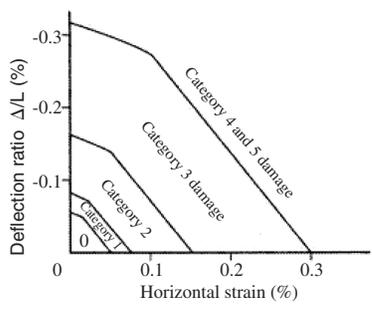
A fundamental difference between these two charts is the use of the parameter deflection ratio (figure 5b) or the angular distortion (figure 5a) as measure for the building distortion due to vertical (differential settlements). The influence of these two approaches on the determination of the tensile strains and thus the damage class is discussed in the following chapters of this paper.

5.2 Deflection ratio

The deflection ratio is defined as the maximum vertical deflection between the tilt line of the building and the imposed settlement curve. It is noted, that the difference between the vertical component and the



(a)



(b)

Figure 5. Design charts from (a) Boscardin et al. and (b) Burland et al.

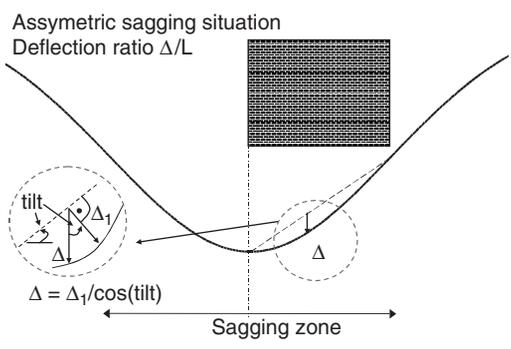


Figure 6. Deflection ratio.

deflection component perpendicular to the tilt line is negligible for practical values of the tilt (see figure 6).

5.3 Angular distortion

By using the LTS method in practical engineering it is recognized, that, dependant on the location of the building in the settlement trough different values for the angular distortions at the outer ends of the building can be derived. This is shown at the example for a building situated asymmetrically in the sagging zone of a Gaussian formed settlement trough due to tunnelling.

The example of figure 7 shows a relation of $\beta_{\text{left}}/\beta_{\text{right}}$ of 1.8, or in other words the angular

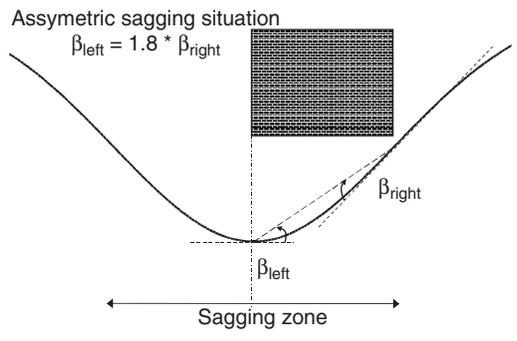


Figure 7. Example determination angular distortion.

distortion at the left end of the building is 1.8 times bigger than the distortion at the right end. The question raises which of the two values to be used as input for the LTS and how the different values for the angular distortion influence the strains.

5.4 Influence of the deflection ratio or angular distortion on the tensile strains

The asymmetric sagging situation of figure 7 is considered. Three type of calculations for different L/H-ratio's are made to investigate the influence on the strains:

- (A) Numerical Timoshenko-beam calculations with the fully imposed ground deflection profile, serving as the "correct" reference for the tensile strains.
- Analytical calculation of the tensile strains with the LTS (fictive point load approach) and the angular distortion (B) or the deflection ratio (C) as input parameter.

Reference is the beam calculation A with the fully imposed Gaussian as it represents the correct strains for including the varying curvatures along the Gaussian profile. Modificationfactors are derived representing the differences in tensile strains according to the deflection ratio fit (model B) and the angular distortion fit (model C) with the reference tensile strains from model A. A modificationfactor > 1 means that the approach overestimates the correct strains from model A. The principle of this study is shown in figure 8.

For the presentation of the results it is distinguished between the influence on the bending strains and the diagonal strains. The difference in strain values between model B, model C and the reference model A is described in terms of modificationfactors which are shown in the figures 9 and 10. Four lines of modificationfactors are given, taking into account the deflection ratio fit and the fit on the maximum, minimum and the average value for the angular distortion for an asymmetric sagging situation ($\beta_{\text{left}}/\beta_{\text{right}}$ of 1.8). The

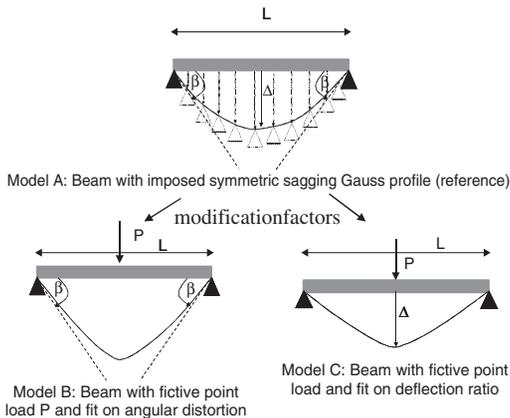


Figure 8. Principle for comparison of angular distortion and deflection ratio approach on the tensile strains.

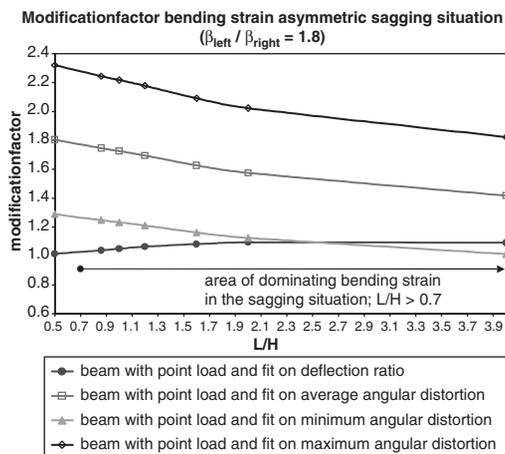


Figure 9. Modificationfactor for bending strains.

average value for the angular distortion is defined as the average value of the angular distortion at the left end and the right end of the building.

The deflection ratio fit leads to a good agreement of the **bending strains** (overestimation of up to 10%). The use of the maximum value for the angular distortion to determine the bending strains leads for the asymmetric sagging situation to an overestimation of up to 120%! The average value for the angular distortion leads to an overestimation of up to 80%. In the asymmetric sagging situation the use of the deflection ratio shows a significant underestimation of the **diagonal strains** of circa 55%. The use of the maximum angular distortion leads to a very good agreement of the diagonal strains with the reference ($\pm 3\%$).

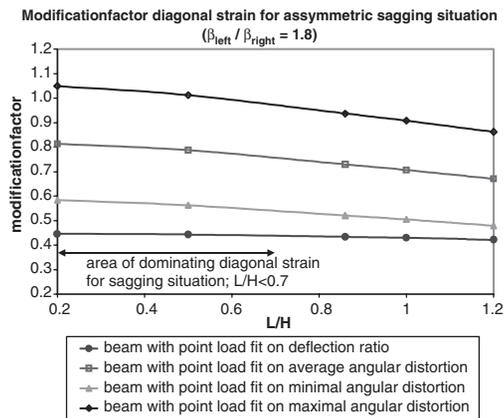


Figure 10. Modificationfactor for diagonal strains

6 CONCLUSIONS

This paper presents results of a review of the currently used empirical, analytical LTS (limiting tensile strain method) for the prediction of settlement induced building damage. The paper discusses the influence of three basic assumptions in the method. The influence on the strain results are described and the following suggestions are made:

- The Timoshenko-beam equations which are used in the current LTS-approach can lead to an underestimation of the tensile strains dependant of the L/H -ratio of the building. The corrected approach, presented in this paper, should be used.
- Neglecting the “cantilever”-effect of a structure proceeding beyond the settlement influence area can lead to an significant underestimation of the tensile strains. For longer structures this effect has therefore to be considered carefully in assessing damage risks.
- The author recommends to use the maximum angular distortion for the determination of the diagonal tensile strains and the deflection ratio to determine the bending tensile strains with the LTS for Gaussian formed settlement profiles. This approach leads to correct determination of the tensile strains with the limiting tensile strain method within practical acceptable bandwidths ($\pm 10\%$).

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