DESIGN THROUGH AN INCREMENTAL APPROACH: THE SWISS EXPERIENCE

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Abstract: *In Switzerland, the current code for structural concrete published in 2003 privileged an incremental approach for design of new members or for assessment of existing structures with respect to a number of topics (shear, buckling, reinforcement detailing through strut-and-tie modelling,...). The incremental approach is grounded on the use of general and sound theories (based on physical models) where the hypotheses performed for their application can be refined as the required accuracy increases. The approach proposes thus to adopt safe hypotheses at first stages of design leading to relatively simple and low time-consuming analyses. In cases where such degree of accuracy is not sufficient, the hypotheses are refined in a number of steps, leading to better estimates of the behaviour and strength of the member.*

Such approach has revealed to be very convenient for design of new structures (where different levels of detail are required as the project evolves from preliminary or conceptual design to a construction project) or for assessment of existing structures, where the structural safety may be found insufficient according to simple design rules.

1. INTRODUCTION

Codes usually face the problem of over-ruling most aspects of design (which is usually time-consuming and leaves little opportunity to designers for using advanced state-of-the art design methods) or of being excessively open (which might be dangerous in the hands of inexperienced designers). In Switzerland, since the introduction of the Swiss codes in 2003, an incremental approach has been privileged with the aim of overcoming the aforementioned problems. The incremental approach provides, in a first stage, simple and safe rules for design. Such rules, as well as the values given for the various parameters, can be refined in further steps by using more accurate (and time-consuming) procedures in case it is judged necessary, see Figure 1. Applications of this design approach to buckling of columns (2nd order effects), shear and punching shear or reinforcement detailing based on strut-and-tie models have led to excellent experiences in Switzerland[1].

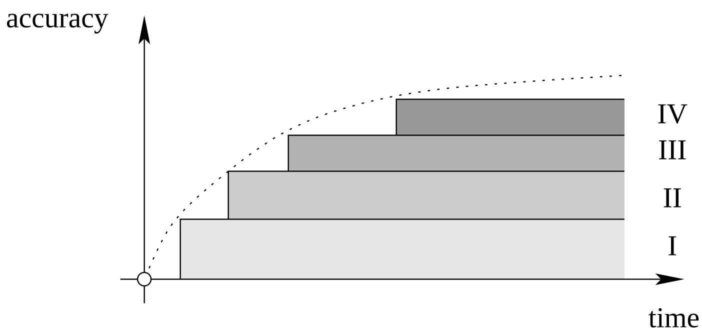

Figure 1: Expected accuracy as a function of time devoted to analyses

With respect to design of new structures, this approach allows to gradually increase the accuracy of the analyses as the project evolves from preliminary design studies to a construction project. This helps expending the necessary time at each design stage. Also, it allows performing refined design for unusual elements with special significance with reference to the structural safety of the structure (such as discontinuity regions or coupling members for instance).

With respect to the assessment of existing structures, the incremental approach has also shown to be very convenient. Existing structures, even if they were correctly designed according to codes of practice at the time they were built, they might not comply with current code recommendations. This does not mean however that such structures are unsafe. Design rules are provided to cover a series of uncertainties and to be applied to a wide number of cases, but they might be excessively conservative in some situations. In these cases, the use of more refined analysis methods to assess the structural safety is fully justified (even if they are more time-consuming) as expensive strengthening can be avoided.

In this paper, the fundamentals of this approach are presented with reference to a practical example (the shear strength assessment of the deck slab of an existing bridge). The gain in the structural strength is investigated from simple procedures to refined (nonlinear finite-element based) analyses, all of them grounded on the same theoretical model.

2. INCREMENTAL APPROACH FOR SHEAR DESIGN IN ONE-WAY SLABS WITHOUT TRANSVERSE REINFORCEMENT

The design equations presented in the Swiss code for structural concrete[1] with respect to one-way shear in members without transverse reinforcement is grounded on the critical shear crack theory[2]. This theory estimates the shear strength (accounting for characteristic material strength and partial safety factors) as[2]:

$$v_{Rd} = \frac{V_{Rd}}{b} = \frac{0.3}{\gamma_c}\sqrt{f_{ck}} \cdot d \frac{1}{1+120 \cdot \dfrac{\varepsilon \cdot d}{d_{g0}+d_g}} \quad (1)$$

where V_{Rd} is the shear strength, b is the width of the member (v_{Rd} being thus the shear strength per unit length), γ_c is the partial safety factor for concrete (1.5 in Europe), f_{ck} is the characteristic compressive strength of concrete (measured in cylinder), d is the effective depth, d_{g0} is a reference aggregate size (16 mm), d_g is the maximum aggregate size (in [mm]) and ε is a reference strain.
The reference strain (ε) is calculated at a depth equal to 0.6 d from the compression face of the member in a control section located at $d/2$ of a support or concentrated load[2]. For its calculation, it is assumed that plane sections remain plane and that concrete exhibits a linear elastic behaviour in compression with no tensile strength. It can be noted that considering the shear strength as a function of a reference strain allows considering the influence of axial forces in the member (prestressing effects or tension forces) in the shear strength.

Although the calculation of the reference strain can be performed analytically, it may be tedious for practical design. Eq. (1) can therefore be simplified assuming a constant depth for the compression zone[2] (equal to 0.35 d) and a linear relationship between the reference strain and the bending moment (prior to reinforcement yielding) leading to:

$$v_{Rd} = 0.2 \cdot \sqrt{f_{ck}} \cdot d \frac{1}{1+\dfrac{50}{d_{g0}+d_g} \cdot \dfrac{f_{yk}}{\gamma_s \cdot E_s} \cdot d \cdot \dfrac{m_d - m_{Dd}}{m_{Rd}-m_{Dd}}} \quad (2)$$

where f_{yk} is the characteristic yield strength of the reinforcing steel, γ_s is its partial safety factor of rebars (1.15 in Europe), E_s is the modulus of elasticity of steel (205'000 MPa), m_d is the design bending moment per unit length acting in the control section, m_{Rd} is the flexural strength and m_{Dd} is the decompression moment (to be considered if prestressing or axial forces are applied, zero otherwise).

This formula can further be simplified for design purposes by considering a (typical) aggregate size of 32 mm, and yield strength f_{yk}/γ_s = 435 MPa (usual value in Europe), which leads to:

$$v_{Rd} = 0.2 \cdot \sqrt{f_{ck}} \cdot d \frac{1}{1 + 2.2 \cdot d \cdot \dfrac{m_d - m_{Dd}}{m_{Rd} - m_{Dd}}} \tag{3}$$

Equation (3) is simple enough to be used in practice, and accounts for the influence of size effect (decreasing nominal shear strength $V_{Rd}/(bd)$ for larger beam depths) and of the bending moment on the shear strength. It can be noted that, in most cases, m_{Dd} can be neglected. For simplified or preliminary analyses, it can furthermore be simplified assuming that reinforcement yields at shear failure. This hypothesis leads to safe results and simplifies the previous equation to:

$$v_{Rd} = 0.2 \cdot \sqrt{f_{ck}} \cdot d \frac{1}{1 + 2.2 \cdot d} \tag{4}$$

whose use is straightforward in practice.

The previous stages followed for derivation of Equation (4), may be used (in reverse order) as an incremental approach leading to the following steps for shear design or assessment:

1. Use of Eq. (4) as simplest and safest estimation of shear strength
2. Use of Eq. (3) with m_d estimated from an elastic analysis and neglecting m_{Dd}
3. Use of Eq. (3) with m_d estimated from an elastic analysis and considering m_{Dd} if applicable
4. Use of Eq. (3) with m_d estimated from an analysis accounting for redistributions considering cracking or reinforcement yielding
5. Use of Eq. (1) with best possible estimation of reference strain ε

3. EXAMPLE OF APPLICATION

Figure 2 shows the cross section of a typical box-girder bridge built in Switzerland in the 70's. In this section, the shear strength of the deck slab (portion between webs) will be investigated following the incremental approach previously introduced.

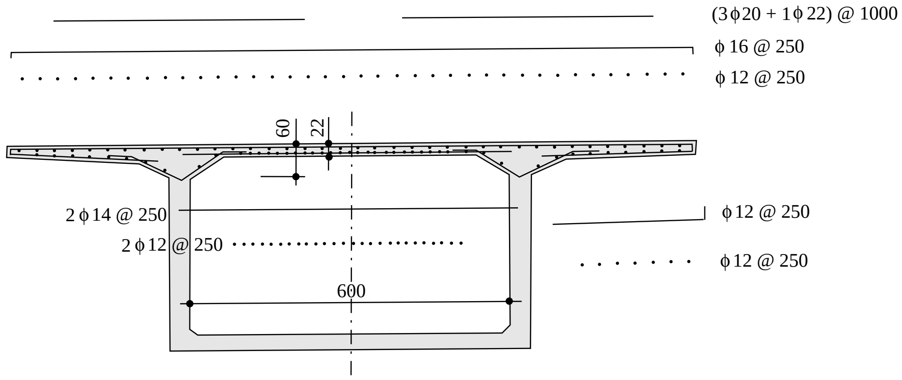

Figure 2: Cross section of investigated box-girder bridge (units in [mm])

The control section and governing load case for shear are shown in Figure 3. Loads are calculated according to the Swiss code[3] SIA 261 (2003) accounting for updated values of traffic loads[4] (for details see reference[5]). Spreading of the wheel forces through the asphalt pavement is neglected at first stage; its influence will be discussed at the end of this section.

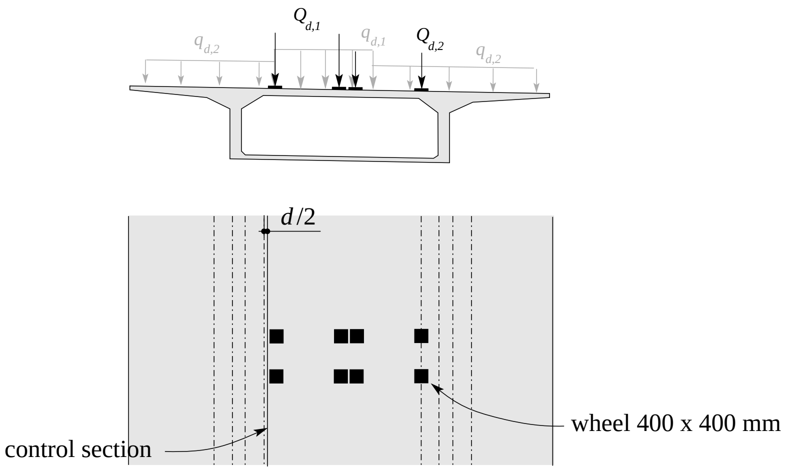

Figure 3: Control section and governing load case (Q_{d1} = 630 kN, Q_{d2} = 300 kN, q_{d1} = 6.75 kN/m^2 and q_{d2} = 1.875 kN/m^2)

3.1 Linear elastic analysis of shear force & safe estimate of reinforcement strain

The maximum shear force per unit length at the control section can be calculated on the basis of a linear elastic analysis[5] as v_d = 235 kN/m. A first estimate of the shear strength can be obtained by using Eq. (4) (reinforcement at yielding) as v_{Rd} = 177 kN/m, which is insufficient to ensure the structural safety of the slab (v_d/v_{Rd} = 0.75).

3.2 Linear elastic analysis of shear force and bending moments & consideration of reinforcement strain on shear strength

Using the same linear elastic analysis previously performed, the corresponding bending moment is m_d = 98 kNm/m. Thus, using Eq. (3) and considering m_{Dd} = 0 (no transverse prestressing) the shear strength results v_{Rd} = 189 kN/m. Although higher than the previous strength, it is still insufficient (v_d/v_{Rd} = 0.80).

3.3 Nonlinear analysis of shear force and bending moments & consideration of reinforcement strain on shear strength

A more refined analysis of the shear forces acting along the control section can be performed by accounting for internal redistributions after cracking or local steel yielding. In so doing, the shear field shown in Figure 4 is obtained, which allows decreasing the shear force to v_d = 222 kN/m with a corresponding bending moment of m_d = 104 kNm/m, leading to a strength v_{Rd} = 185 kN/m. This value is still not sufficient to ensure the structural safety (v_d/v_{Rd} = 0.85).

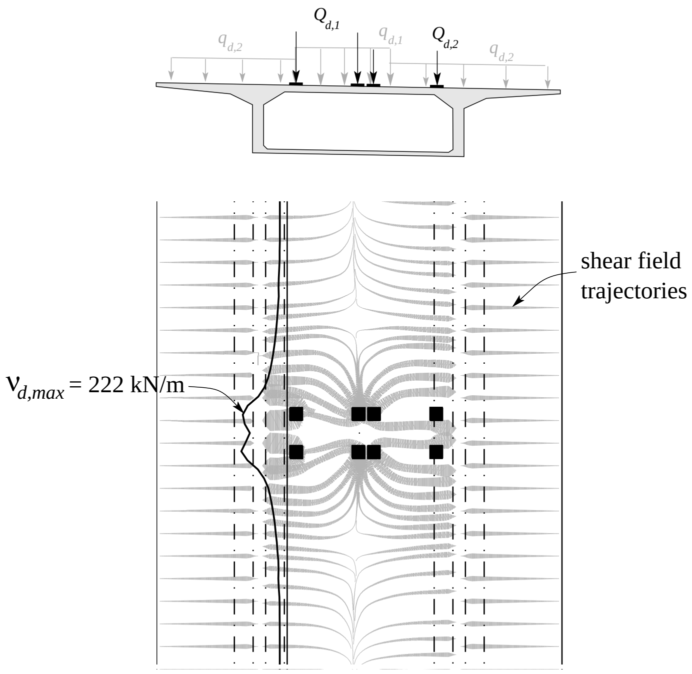

Figure 4: Shear field and shear force distribution along the control perimeter after a nonlinear analysis

3.4 Further considerations

Further considerations affecting the shear strength can also be accounted in the strategy of increasing accuracy. In this case, the previous analysis (Fig. 4) can be redone by considering the spreading of the wheel forces throughout the asphalt pavement layer[5]. Accounting for a slope 1:2 for such spreading and a pavement thickness of 10 cm, see Figure 5, the size of the wheels can be increased to 500×500 mm, leading to v_d = 178 kN/m and m_d = 104 kNm/m.

Introducing the value of the bending moment into Eq. (3), v_{Rd} results 183 kN/m, which is sufficient to ensure the structural safety with respect to shear of the inner deck slab (v_d/v_{Rd} = 1.03).

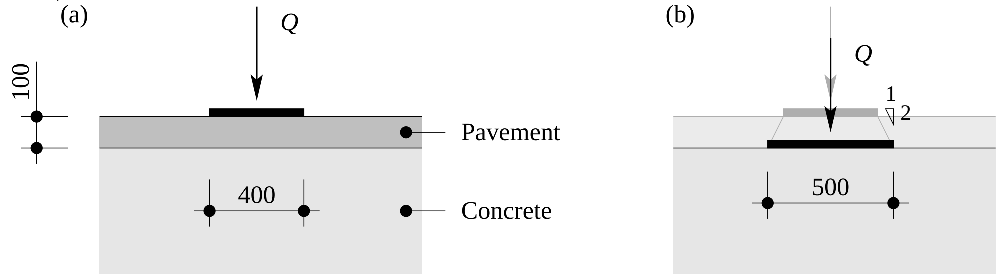

Figure 5: Wheel load spreading through asphalt layer

3.5 Summary of results

The results of this example show that the calculated safety of the deck slab increases as the hypotheses performed for application of the theory are progressively refined. The gain in the strength (neglecting load spreading through the asphalt pavement) is however moderate, with values of v_d/v_{Rd} increasing from 0.70 to 0.85. This shows that even coarse estimates of the strength may still provide realistic values, but that the accuracy of the analysis can be easily refined by performing some supplementary analyses.

4. CONCLUSIONS

In this paper, the main ideas of the incremental approach for design and assessment of structures are presented and discussed. The main conclusions of the paper are:

1. The incremental approach is based on the idea of providing safe (but realistic) values of the strength of structural members when little time is devoted to the analysis. The accuracy can be increased when additional analyses are performed
2. This is consistent with the use of sound theories based on physical models where the hypotheses performed for their application can be progressively refined
3. Such approach is convenient for design or assessment of structures:
    a. With respect to design, it allows increasing the accuracy of the analyses as the project evolves from a conceptual design to a construction project

   b. With respect to the assessment of existing structures, it allows refining some hypotheses adopted for design (introduced to cover a broad range of cases). Thus, increasing the time devoted to the analyses is in most cases justified as expensive (and unnecessary) strengthening can be avoided

4. The current Swiss code for structural concrete proposes to follow the incremental approach with respect to shear, punching shear, buckling and strut-and-tie modelling. Very positive experiences have been obtained, encouraging the use of this approach in other domains

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