Restoration Design for RC Slab Bridges by AASHTO LRFD

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Abstract: Most bridges in the world are constructed before several decades ago and their load carrying capacities have been reduced due to many reasons. To assess their conditions, the original design documents must be available. If not, performance assessment is a difficult task. Restoration design is important to estimate initial conditions of bridges. Most countries, especially developing countries, use AASHTO LRFD method for the design of bridge structures. Thus, in this study, a flow of restoration design of RC slab bridges following AASHTO bridge design specification is presented.

Key words: Design restoration, RC slab bridges, Performance assessment, Initial conditions

1. Introduction

Design of bridge structure is a complex engineering problem which includes design of structural systems, selection of design manuals and standards. During design of bridges, an internationally accepted manuals and standards have to be referred. Most bridges in the world are constructed before several decades ago and they are in various states of deterioration. The problem of aging, overloading and rapidly deteriorated bridges is an issue most countries are facing. Because of these, their load carrying capacity has been reduced. Hence, assessment of bridge’s condition is important task in bridge management.

To accomplish this task, the original design document, drawing and plan must be available at hand. In the absence of such data it is difficult to know the initial condition of the bridge unless and otherwise advanced technique of bridge monitoring system in the country is used.

If the design data is lost, inaccessible or a change exists in the design specification used, it will be a common problem facing bridge engineers to assess bridge’s performance. It is mainly due to absence of any kind of readymade bridge information. Thus, a flow of restoration design for RC slab bridges is important to estimate initial condition of bridges (steel and concrete strengths used, reinforcement size and spacing, etc) and is a necessary tool to estimate current condition of bridges. Even if the design manuals and specifications are known, construction efficiency and certainty in comply with the standards affect the restoration process.

Restoration design is a process of accurately describing the initial condition (design values) of a structure from its current condition (actual values). Restoration design uses design values. On the other hand, if deflection is used as additional data, it reflects the present actual values. Also an indirect method for the estimation of yield strength of steel is needed. The required dimensions of the structure are determined through measurements.

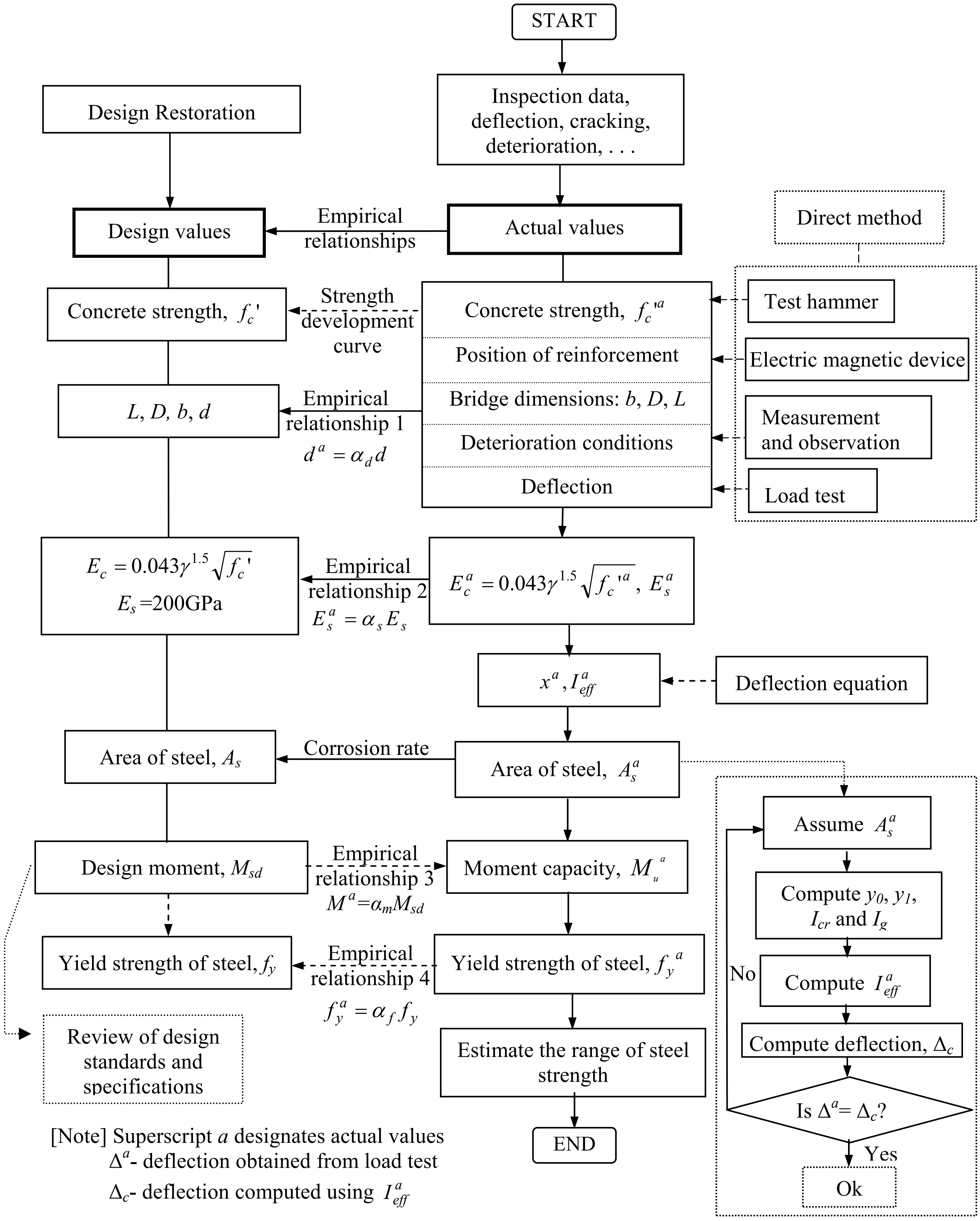
Non-destructive tests for the estimation of current concrete strength, mid-span deflection of the bridge from load test and position of reinforcing bars using an electric magnetic device are main inputs for the restoration design process. From compressive strength development curves, design value of concrete strength is estimated.

In this study, a flow of restoration design based on the deflection of the bridge from load test is presented. Measurements shall be made at locations where maximum response is expected, i.e., the incremental instantaneous mid-span deflection of the bridge due to applied load needs to be measured. Additional measurements shall be made if required.

2. Method of Restoration Design

Direct and indirect methods are used for the restoration process. Measurements and observations are one of the direct methods to be used. For computation of live load force effects on the structure, Green’s function for RC beams are applied. Based on the flow of restoration design of concrete bridges [1], the general flow chart for restoration design of RC slab bridges of known effective depth is shown in **Fig. 1**. For unknown effective depth, load test should be conducted at least at two positions. The assumptions used are as follows.

- Locations of the reinforcing bars will be determined using an electric magnetic device.
- Current concrete strength is obtained by a test hammer.
- Deflection of the beam is obtained from load test.
- Linear strain distribution, i.e., no severe bond deterioration between concrete and re-bars.
- The effect of live loads on the bridge is computed based on AASHTO LRFD bridge design specification.



[Note] Superscript *a* designates actual values
Δ^a- deflection obtained from load test
Δ_c- deflection computed using I_{eff}^a
I_{eff}^a - effective moment of inertia based on assumed value of A_s^a

Fig.1 Flow of restoration design of RC slab bridges for known effective depth

3. Restoration Design of RC Slab Bridges

3.1 Analysis

Vehicular live loading on the roadways of bridges or incidental structures based on AASHTO LRFD bridge design specification, designated HL-93, is used for the computation of live load force effects. It consists of a combination of the design truck or design tandem, and design lane load. A lane load of 9.3kN/m uniformly distributed in the longitudinal direction is used. The dead load is computed based on the actual dimensions of the bridge. The design vehicular loads are shown in **Fig.2**.

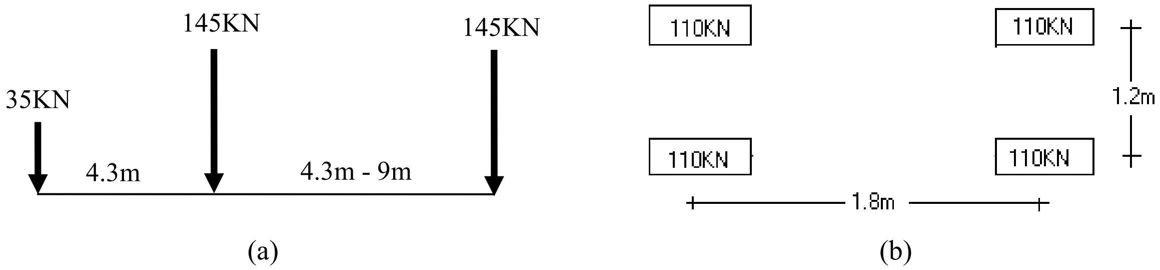


Fig.2 Design vehicular (a) truck and (b) tandem loads

The equivalent live load width of longitudinal strips per lane for both shear and moment may be determined in accordance with AASHTO bridge design specifications. For the calculation of live load effects on the bridge, the concept of influence line is used and the maximum effect is selected for further analysis.

To estimate the ultimate design moment, load factors of 1.25 for dead load, 1.75 for live loads and an impact factor of 1.33 are used.

3.2 Computation of effective moment of inertia

To compute the effective moment of inertia, the variation in the neutral axis depth and moment of inertia along the bridge's span is taken into account. The neutral axis along the longitudinal line is not constant due to the tensile strength of concrete. For uniformly distributed loads, since the neutral axis depth is related to bending moment, a parabolic neutral axis and variable moment of inertia along the longitudinal direction are assumed.

For old structures, the distribution of the neutral axis is independent of load position, and it doesn't move with load and is assumed to be unchanged since the section is already cracked by the maximum possible load experienced in the past. For the derivation of neutral axis depth variation along its length, consider the longitudinal cross section shown in **Fig.3**. For cracked and uncracked sections, the neutral axis depth and moment of inertia are given in Eqs. (1), (2). In general, the neutral axis depth and the moment of inertia at a section are given in Eq. (3).

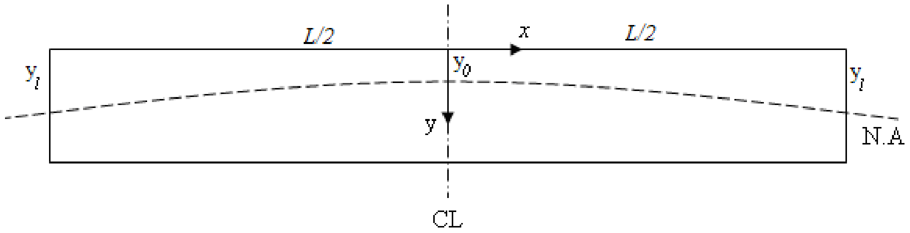


Fig. 3 Variation of neutral axis depth of existing RC slab bridge

$$0.5by_0^{\ 2} = nA_s(d-y_0)\ ;\ I_{cr} = \frac{by_0^{\ 3}}{3} + nA_s(d-y_0)^2 \tag{1}$$

$$y_1 = \frac{nA_sd + 0.5bh^2}{nA_s + bh}\ ;\ I_g = \frac{bh^3}{12} + bh(\frac{h}{2} - y_1)^2 + nA_s(d-y_1)^2 \tag{2}$$

Boundary conditions:

At x=0, $\bar{y} = y_0$, at x=L/2, $\bar{y} = y_1$ and at x=- L/2, $\bar{y} = y_1$

$$\bar{y} = \frac{4(y_1 - y_0)}{L^2}x^2 + y_0 = y_1\left(\frac{2x}{L}\right)^2 + y_0\left(1 - \left(\frac{2x}{L}\right)^2\right) \tag{3}$$

where: $\bar{y}$ - neutral axis depth at a section, measured from the top fiber (mm)

L- length of the beam (m)

d- effective depth (mm)
h- total depth (mm)
b- width (mm)
A_s- area of steel in tension (mm^2)
n -modular ratio, E_s/E_c
E_s, E_c-Young's modulus of steel and concrete respectively
x- distance measured from the mid-span of the beam (m)
y_0, I_{cr}- neutral axis depth (mm) and moment of inertia of the cracked section (mm^4)
y_1 , I_g- neutral axis depth (mm) and moment of inertia of the uncracked section (mm^4)

Deflection may be computed using the modulus of elasticity for concrete as specified in AASHTO and taking the moment of inertia given in Eq. (4). The deflection of the bridge computed using elastic beam deflection equation should be the same with that of the actual deflection measured during load test. This problem is solved by a trial and error procedure.

$$I_{eff} = \left(\frac{M_{cr}}{M_a}\right)^3 I_g + \left[1 - \left(\frac{M_{cr}}{M_a}\right)^3\right] I_{cr} \leq I_g \tag{4}$$

where: I_{eff} - effective moment of inertia (mm^4)
M_{cr} - cracking moment (kN-m), $M_{cr} = f_r I_g / y_t$, $f_r = 0.63\sqrt{f_c'}$
f_r - modulus of rupture of concrete (MPa)
y_t - distance from the neutral axis to the extreme tension fiber (mm)
M_a - maximum moment in a component at the stage for which deformation is computed (kN-m)

3.3 Estimation of actual yield strength of steel

The design value of yield strength of steel is discrete whereas the actual value obtained from restoration design process is scattered. Thus, from the result, the range of f_y can be estimated. The basic assumption considered in the estimation of actual yield strength of steel is that the flexural capacity of the section is estimated by considering the effect of yielding moment and the section is triangular with tension steel only. Thus, the following equations hold.

$$M^a = A_s^a f_y^a (d - y^a/3) \tag{5}$$

$$y^a = \frac{\varepsilon_c^a}{\varepsilon_c^a + \varepsilon_s^a} d \,,\quad \varepsilon_c^a = f_c'^a / E_c^a ,\quad \varepsilon_s^a = f_y^a / E_s^a \ \text{ and } \ E_c^a = 0.043 \gamma_c^{1.5} \sqrt{f_c'^a} \tag{6}$$

$$(f_y^a)^2 + (0.667 f_c'^a \, E_s^a / E_c^a - m_d) f_y^a - (m_d f_c'^a \, E_s^a / E_c^a) = 0 \tag{7}$$

Upon simplification, Eq. (7) becomes:

$$(f_y^a)^2 + (26.292 \alpha_s \sqrt{f_c'^a} - (\alpha_m + 1) m_d) f_y^a - 39.559 \alpha_s (\alpha_m + 1) m_d \sqrt{f_c'^a} = 0 \tag{8}$$

where: M_{sd} - ultimate design moment (N-mm/m)
M^a -actual flexural capacity of the section (N-mm/m)
$m_d = M_{sd} / A_s^a d$ (N/mm^2)
A_s^a -actual area of steel (mm^2/m)
f_y^a -actual yield strength of steel (MPa)
$f_c'^a$ -current concrete strength (MPa)
ε_s^a , ε_c^a -actual tensile strain in the steel and compressive strain in the concrete respectively

y^a - neutral axis depth (mm) computed using Eq. (3)
α_s- ratio of E^a_s to E_s (E_s=200MPa)
$\alpha_m = M^a / M_{sd}$
γ_c -unit weight of concrete (24kN/m^3)

3.4 Regression Analysis

From Eq. (8), it is observed that the yield strength of steel is affected by different parameters. These are: compressive strength and Young's modulus of concrete ($f_c'^a$, E_c), Young's modulus of steel (E_s) and m_d (moment capacity, area of steel and effective depth). The effect of each random variable on f_y is investigated and empirical relationships using quadratic interpolation are obtained. The empirical relationships describing the effects of $f_c'^a$, E_s and m_d on f_y are given in Eqs. (9), (10) and (11) respectively. The effect of m_d on f_y is shown in **Fig.4**. A general empirical formula for the estimation of the actual yield strength of steel is given in Eq. (12). This predicted value f_y^a of the current yield strength is used to estimate the current load carrying capacity of the bridge.

$$f_y^a = -0.000217 m_d^2 + (0.00297 f_c'^a + 1.166) m_d + 7.825 \tag{9}$$

$$f_y^a = -0.000214 m_d^2 + (0.164 \alpha_s + 1.097) m_d + 7.863 \tag{10}$$

$$f_y^a = -0.000215 (\alpha_m + 1)^2 m_d^2 + 1.216 (\alpha_m + 1) m_d + 8.090 \tag{11}$$

$$f_y^a = -0.000215 (\alpha_m + 1)^2 m_d^2 + (0.000990 f_c'^a + 0.0534 \alpha_s + 1.141)(\alpha_m + 1) m_d + 7.956 \tag{12}$$

The empirical formulae given in Eqs. (9)- (11) are obtained by using average values of α_m=0.025, α_s=0.975 and $f_c'^a$ =28MPa. For the interpolation function given in Eq. (12), the following ranges of parameters are used. These are: $f_c'^a$ = 24MPa-32MPa, α_s=0.95-1.0 and α_m=0-0.05.

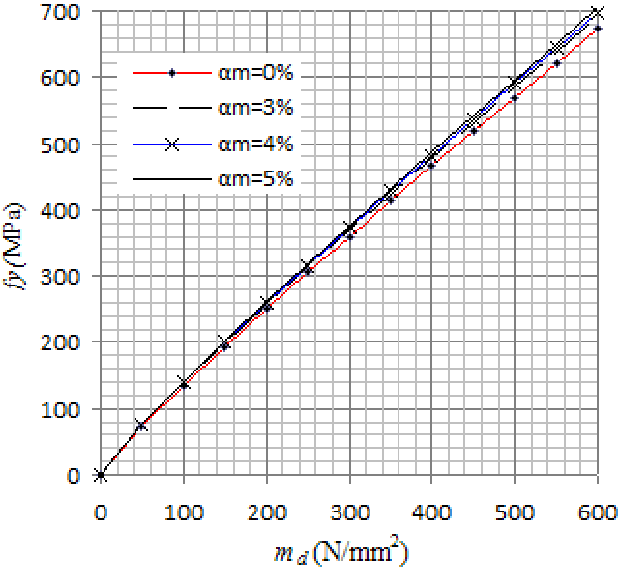


Fig. 4 Effect of α_m *on* f_y

3.5 Design value of f_y

The actual value of f_y is obtained by using Eq. (5). In this case, the ultimate design moment (M_{sd}) and area of steel, A_s are used. The value of f_y is selected from the nearest small discrete nominal value. The discrete nominal yield strength is shown in **Table 1**. Alternatively, in Eq. (12) substitute α_m by ($-\alpha_a$) and put $\alpha_s=1$ to obtain design value of f_y. There is a difference in the predicted value of f_y due to the assumed values of α_s, α_m and α_a.

$$A_s = A_s^a/(1-\alpha_a)\,,\quad d = d^a/(1-\alpha_d) \tag{13}$$

where: α_a -ratio in reduction of cross-sectional area due to deterioration
α_d -ratio considering the change in effective depth. For simplicity, α_d is taken as zero.

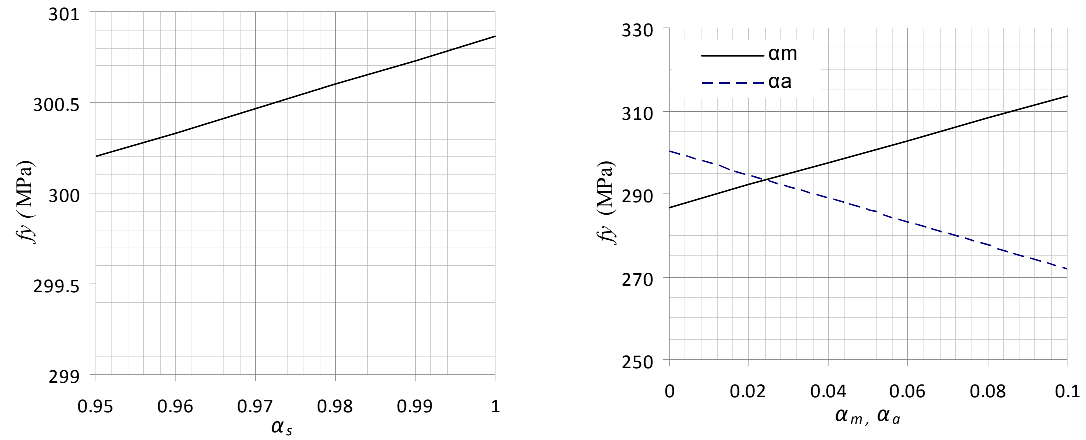
Table 1 Discrete nominal yield strength f_y

AASHTO M31 M Grade	Grade 300	Grade 420	Grade 520
Tensile strength, min. MPa	500	620	690
Yield strength, min. MPa	300	420	520

For a 10m RC slab bridge the incremental instantaneous mid-span deflection due to applied load, from simulation, is obtained and the actual area of reinforcing bar is computed. The actual yield strength of steel is calculated using the interpolation function given in Eq. (12). **Table 2** shows calculation results. Thus, the nominal yield strength of steel from **Table 1** is 300MPa. Moreover, the effect of each random variable is investigated and the curves showing the effect of α_s, α_m and α_a on f_y are plotted in **Fig.5**.

Table 2 Actual values of a 10m RC slab bridge

Parameter	Value	Parameter	Value	Parameter	Value
Span length	10400mm	M_{sd}	647.77kN-m/m	α_m	0.05
Total width	7320mm	A_s^a	5600mm^2/m	α_a	0.05
Effective depth	490mm	α_s	0.95	A_s	5895mm^2/m
W_e (strip width)	3203mm	$f_c'^a$	28MPa	f_y^a	300.185MPa



(a)　　(b)

Fig. 5 Effect of α_s, α_m and α_a *on* f_y

4. Conclusion

1) A restoration design flow is presented following AASHTO LRFD bridge design specification and it is used to establish a methodology for the capacity performance assessment of existing RC slab bridges.
2) Empirical formulae for the estimation of yield strength of steel by considering the effects of concrete strength, Young's modulus of steel and moment capacity have been obtained.

References

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