CHAPTER 5

SOME GENERAL PROBLEMS OF BRIDGE REHABILITATION

5.1 General Considerations

Although rehabilitation problems concerning a given bridge structure should be considered individually, i.e., depending on the situation, there are several general problems that are required to be solved in every case. These general problems can be formulated as a set of the following fundamental questions:

(a) does the bridge need to be utilized at all?
(b) how long is the bridge predicted to be utilized?
(c) what is the technical condition of the bridge and its safety?
(d) what are the current and predicted traffic conditions (i.e., the changes in traffic intensity and speed, weights of the vehicles and their types, etc.)?
(e) is the bridge functionally adequate for current or predicted traffic conditions?
(f) is the load-carrying capacity adequate for the current or predicted live loads (i.e., mainly road or railway traffic) and other types of loads (e.g., wind load) acting on the structure?
(g) what are the structural and material possibilities to repair, rehabilitate, strengthen or modernize the bridge geometrically?
(h) what are the costs of the above mentioned actions, including the costs of traffic difficulties, compared with the costs of the new bridge?

(i) what are the maintenance costs before and after the repair, rehabilitation, strengthening or geometrical modernization of the bridge?
(j) what are the historical merits and aesthetics of the bridge?
(k) what is the role of the bridge in the development plan concerning the given town or out-of-town areas?

The questions denoted by (a), (b), (d) and (e) may be classified into the utilization group of problems, the questions denoted by (c), (f) and (g) — into the structural and material group, while the questions denoted by (h) and (i) — into the economical group. The questions denoted by (j) and (k) belong to the architecture and urban planning group of problems. It is obvious that all the above groups have references to each other and should be considered when making decision concerning bridge evaluation and to determine the technical and economical actions needed to enable safe utilization of the bridge according to the required traffic conditions. The decision making process is schematically illustrated in Fig. 5.1.

Each of the above listed questions demand some comments to explain their technical and economical meanings. Some of the problems are more widely presented in the next sections of this chapter (cf. Secs. 5.2–5.5).

The question denoted by (a) seems to be somewhat controversial and nonsensical. However, in cases concerning mostly old bridges, further utilization may not be needed due to the following reasons:

- a road or railway line is inactivated or closed to normal traffic, e.g., when the bridge is located along the industrial road to a quarry or mine that is shutdown,
- when the location of the existing bridge is not in accordance with current development plans and the structure is earmarked to be removed, e.g., an old viaduct (overpass structure),
- when the bridge, especially its superstructure, is completely destroyed (e.g., by a military action) and should be replaced by a new structure.

Of course, some other reasons indicating unprofitableness of bridge utilization may also occur. When the answer to question (a) is “not”, the bridge can remain in place or it can be wholly or partially disassembled. Some structural members can be used for other construction purposes,

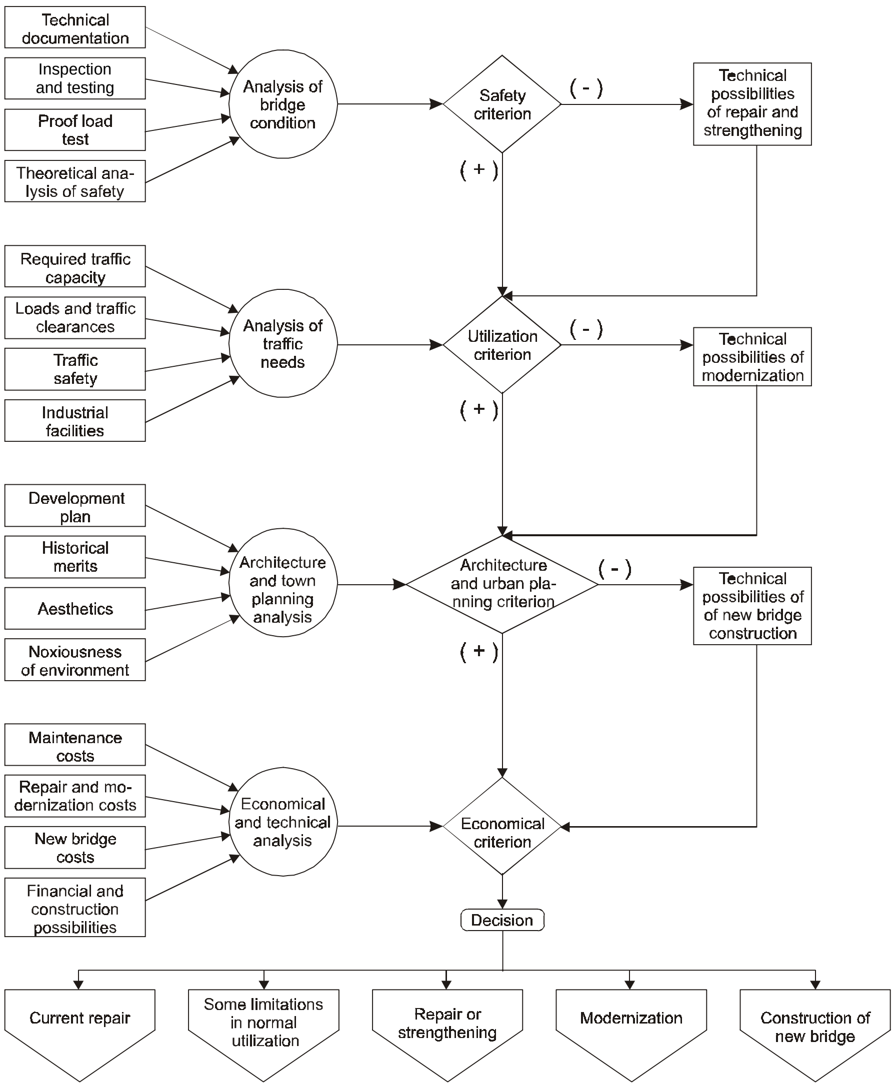

Fig. 5.1 Decision making process for evaluation of the bridge and its further safe utilization.[5.1]

some parts of the materials can be recycled. However, when the historical merits of the bridge are particularly valuable (the answer to question (j) is required), the bridge can be subjected to restoration and presented as an historical structure. In other words, the whole bridge or some of its parts can be arranged in the form of a specific "museum piece", e.g., in the case of Alsea Bay Bridge[5.2] or the first fully-welded bridge in the world completed in 1929 over the Słudwia river near Łowicz, central Poland.[5.3]

However, if the answer to question (a) in a great majority of cases is "yes", then the answers to questions (b)–(k) should be formulated.

Answer to the questions (b), (d), (e) and (k) are normally based on the development plan as well as the traffic studies (which are beyond the scope of this book) of a given area.

Depending on the technical condition, structural and functional adequacy and required service (mostly traffic) conditions as well as the required technical service life, different technical actions may be undertaken, such as local or major repair, strengthening, widening of the deck, replacement of the whole bridge superstructure, rebuilding of the bridge piers including foundations, etc.

The technical condition of the bridge and its load-carrying capacity and safety (questions (c) and (f)) are usually estimated with the use of techniques briefly presented in Chapters 3 and 4 as well as using various theoretical analyses, briefly presented below (Sec. 5.2).

Special attention should be given to questions (g) and (h), which are both multi-component problems and have many references to each other. They are also of technical and economic nature. It should be pointed out that in the economic analysis, the costs connected with traffic difficulties during the construction work should be taken into account. The most important aspect of bridge rehabilitation, strengthening or geometrical modernization that makes it different from the construction of a new bridge, is that it can be performed under normal traffic, some traffic limitations (e.g., closure of one lane) or when the bridge is closed to traffic during the period required for work on the bridge. Therefore, depending on the individual situation, rehabilitation of the existing bridge may require the construction of a temporary bridge (i.e., by-pass bridge) located in the vicinity of the rehabilitated structure to enable the road or railway traffic to proceed in some cases, or the traffic may be rerouted through other existing neighboring bridges. The above situation can be considered as an example to indicate that the additional costs resulting from disturbances to normal traffic are an important component of the total rehabilitation costs. In any case, traffic management should be developed as an inherent element in the rehabilitation project.

In many cases, especially when the technical condition of the bridge is estimated to be relatively low but its further utilization is necessary because of transport and social needs, it is recommended to compare the costs of rehabilitation and modernization with the costs of construction of a new bridge (question (h)). In certain cases, replacement of the old structure by a new one is economically and technically justifiable. In many situations, the replacement concerns some parts of the structure only. For instance, when the bridge deck is required to be widened to add new lanes, the whole of the old deck may be replaced by the new one while the main girders or other main structural members remain the same[5.4] or are adequately strengthened (cf. Chapters 6 and 7).

It should also be mentioned that the maintenance costs before and after rehabilitation or modernization should be analyzed (question (i)) after taking into account the predicted period of bridge utilization. The maintenance costs may be sometimes higher after rehabilitation, e.g., due to heavier traffic than before, replacement of some concrete elements by steel ones, etc. On the other hand, an increase in the rehabilitation costs in many cases resulting from the use of materials of high quality, is justified by a decrease in the maintenance costs during the years of further utilization of the bridge.

Some other economical problems connected with bridge rehabilitation are presented in Sec. 5.3.

The structural and material possibilities for rehabilitation of the bridge should be carefully analyzed (question (g)).

The structural possibilities are closely connected with the structural system of the bridge. In some cases, the system remains in its original form after rehabilitation, but in many situations, the system is changed during rehabilitation or modernization to improve the durability of the bridge, e.g., by providing continuity to the concrete superstructure over the bridge piers (cf. Sec. 3.1, Fig. 3.2). Moreover, depending on the structural system, bridge rehabilitation or modernization may vary in complexity. For instance, when the concrete bridge superstructure consists of a series of parallel precast stringers or beams, their repair or replacement is easier than in rehabilitation of a concrete superstructure constructed in the form of a voided slab cast-in-place. The structural system can also affect the sequence of the rehabilitation or modernization works as well as traffic management during these works. For instance, when the superstructure of a highway bridge consists of two longitudinally separated, parallel structural parts, the two-way traffic may temporarily proceed through one structural part only.

Some other structural problems concerning bridge rehabilitation or modernization are presented below (Sec. 5.2).

The possible materials for bridge repair and rehabilitation are also of prime importance. There are a great variety of high-quality products available for bridge repair. There are also many techniques and relevant equipment of various types for bridge rehabilitation and strengthening (cf. Chapters 6 and 7). Therefore, choice of the appropriate material should be preceded by an extensive analysis of the properties of the repair material and the costs of the material, in order to select an optimum solution from both technical and economic points of view. It should be, however, emphasized that the different repair materials may not be chemically and physically compatible. Therefore, a selection of whole repair systems offered by many highly specialized firms is recommended.

Some other problems concerning material solution for bridge repair and rehabilitation are presented below (Sec. 5.4).

5.2 Analytical, Structural and Design Problems

As mentioned above, the analytical, structural and design problems concerning bridge repair, rehabilitation and modernization are very specific and generally different from the problems required to be solved during the

Table 5.1 Fundamental differences between analytical, structural and design problems concerning bridge repair, rehabilitation or modernization and design and construction of new bridges.

Fundamental problems to be solved	Bridge repair, rehabilitation or modernization	Design and construction of new bridge structures
1. Estimation of the functional adequacy for current or predicted traffic conditions.	Yes(1)	No(2). All geometrical parameters are assumed according to traffic, navigation or other needs.
2. Estimation of the required load-carrying capacity of the bridge.	Yes	No. Required load-carrying capacity is a fundamental design criterion.
3. Estimation of the technical condition of the bridge.	Yes	No. Current, more or less routine inspection during construction stages.
4. Properties of the structural materials assumed for statical calculations and dimensioning.	In general, the actual properties are determined experimentally "in situ" or on the specimens taken from the structure.	In general, material characteristics are taken from the relevant design standards.
5. Properties of the repair materials.	In general, the properties are assumed according to the manufacturer information or sometimes checked experimentally.	No. In some particular cases, when damage occurs during construction, repair materials can be used.
6. Model for statical calculation.	The calculation model can be the same as in the original design process or more complex (e.g., three dimensional) than the original one due to the use of modern calculation technique (i.e., with computers).	In general, no changes in the calculation model are included when the relevant design model is selected.

Table 5.1 (*Continued*)

Fundamental problems to be solved	Bridge repair, rehabilitation or modernization	Design and construction of new bridge structures
7. Traffic management during building works.	Special project should be developed. The works may be performed under normal traffic, under some traffic limitations or when the bridge is closed to traffic. Construction of bypass bridge is necessary in some cases.	No. In general, no major traffic problems occur, excluding some traffic disturbances in cases of construction of new bridges in urban areas.
8. Construction and material costs.	Exact costs, especially the material ones, are difficult to determine prior to work on the bridge (e.g., the actual volume of deteriorated concrete needed to be replaced can only be determined during the works itself).	The construction costs, especially material costs, can be determined exactly.
9. General economics.	In some cases, the costs of rehabilitation or modernization of the bridge should be compared with the costs of a new bridge (i.e., bridge replacement costs).	In general, the costs of various structural solutions are compared to each other.
10. Design standards and other regulations.	The design standards and other regulatory requirements dating back to the period of the bridge design and construction should be taken into account and compared with current ones.	The current design standards and other relevant technical regulations have to be observed.

(1) Yes — means the problem needs to be solved.

(2) No — means the problem does not need to be solved.

design and construction of new bridges. In many cases, they are even more difficult than those related to new structures.

The fundamental differences between the above problems concerning bridge repair, rehabilitation or modernization and design of new bridges are listed in Table 5.1.

The information listed in Table 5.1 is not complete (some other problems can be certainly included) and of a general nature. However, it evidently indicates that all the technical actions concerning bridge repair, rehabilitation or modernization always concern existing bridges, which are normally utilized through a certain period, in other words, bridges having a history of service, whereas the construction of a new bridge is a starting point to the history of the bridge. This fundamental and probably somewhat philosophically expressed difference leads to the many technical and economical consequences presented below.

Excluding routine bridge repair, the relevant calculations should be performed prior to bridge rehabilitation, strengthening or geometrical modernization. A key problem is the structural model assumed for the calculations. As mentioned in Table 5.1 (No. 6), there are in general two main options, namely:

(1) the use of a model assumed for design and dimensioning of the bridge,
(2) the use of a more complex model than that used for design.

Rehabilitation, improvement in load-carrying capacity or geometrical modernization of the bridges usually concern old structures. They have been designed in the years when the more advanced calculation models are not used in the design process because of their labor-consuming nature resulting from the lack of appropriate calculating tools such as computers. Implementation of computer-aided design and its common use allows more complex structural models for statical or other calculations to be applied, e.g., the three-dimensional, spatial models instead of the one-dimensional (e.g., beam) or two-dimensional (e.g., plane frame) ones. This possibility is of prime interest especially in cases of old bridges in relatively good condition but requiring strengthening because of heavy traffic and an increase of vehicular weights compared to previously designated service conditions. It should be pointed out that a safety margin in the load-carrying capacity can result from the calculation model; the use of more advanced models representing the true structure more exactly may reveal the fact that the required strengthening is not necessary. Therefore, the structural model assumed for calculation has its technical and economic consequences. In general, the use of more advanced models leads to economic profits.

There are many structural models for bridge calculation and a great variety of relevant computer programs. Their presentation is beyond the scope of this book. However, it is worth indicating generally the various models and methods which can be used for bridge calculation. They are exemplified in Table 5.2 by the methods concerning calculation of slab and girder (or stringer) concrete bridge superstructures.

Detailed presentation of the criteria for the selection of an adequate calculation model is beyond the scope of this book. However, it should be emphasized that one-dimensional model (i.e., beam model) is too simple and does not allow the determination of the transversal load distribution in bridge structure. Two-dimensional or three-dimensional models should be applied with the use of the relevant, commonly available computer programs (software). In general, the two-dimensional models are applied to the calculation of the whole superstructure, whereas the three-dimensional models are used for the analysis of certain parts of the structure, e.g., the anchorage zone in prestressed concrete bridges. One of the fundamental criteria in selecting a calculation model for theoretical analysis is the mutual relation between the transversal (y-direction) and the longitudinal (x-direction) flexural stiffness of the superstructure:

$$\propto = \frac{(EJ)_y}{(EJ)_x}\,. \tag{5.1}$$

The case when $\propto \approx 1$ corresponds to the isotropic plate model, when $0 < \propto < 1$ corresponds to the orthotropic plate model, and when $\propto = 0$ corresponds to the situation where no transversal interaction between the

Table 5.2 Fundamental methods and models for calculations of slab and girder concrete bridge superstructures.

A. Slab bridges	B. Girder or stringer bridges
I. Bar models (a) one-dimensional model (beam) (b) two-dimensional model (grid)	I. Bar models (a) one-dimensional (beam) (b) two-dimensional (grid)
II. Plate models (a) isotropic plate (b) orthotropic plate (c) combined (e.g., with membrane bending effects in the plate)	II. Surface models (a) orthotropic plate (b) combined models (e.g., with membrane bending effects) (c) FEM⁽¹⁾ models (d) other approximate models (e.g., Trost's method[5.5])
III. FEM two-dimensional model	III. Three-dimensional models (a) FEM method (b) combined models (e.g., plate with membrane bending effects in whole structure and finite strip method in some of its parts) (c) strut and tie method (three-dimensional truss model)
IV. Three-dimensional models (a) FEM method (b) strut and tie method (three-dimensional truss model)	

(1) FEM — Finite Elements Method

beam elements of the superstructure is observed. The relevant example concerning the precast and composite concrete bridge superstructures is shown in Fig. 5.2.

The other important calculation problems are material and structural characteristics assumed for analysis. As mentioned in Table 5.1, in cases of existing bridges required to be rehabilitated, strengthened or geometrically

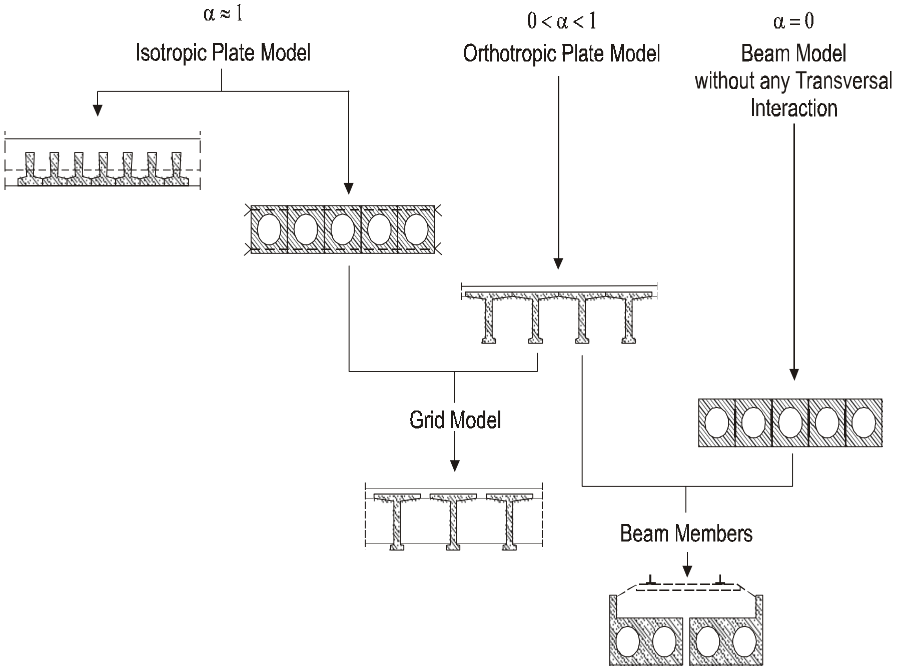

Fig. 5.2 Calculation models for precast and composite concrete bridge superstructures.[5.6]

modernized, the actual properties of the structural materials, taken from the appropriate "in situ" or laboratory tests (cf. Chapter 4), should be assumed for theoretical considerations. Moreover, the structural defects and material weakening affecting a reduction in the flexural and torsional stiffness of the structure and its individual members (e.g., the main girders, roadway slab, floor beams, etc.) as well as influencing their strength, should also be taken into account in the analyses.

It should also be mentioned that the structural model assumed for the statical calculations can differ in some situations from that used for the design of the original bridge not only because of the availability of new calculation techniques, but also due to some changes planned in the structural system itself, e.g., by providing structural continuity over the piers during bridge rehabilitation.

A serious problem also required to be solved during the design process prior to bridge rehabilitation or structural and functional modernization is a change in the distribution of internal forces in the structure resulting from active methods of strengthening, e.g., strengthening by means of external prestressing tendons (cf. Chapter 6). Redistribution of the internal forces and its influence on the behavior of the structure is especially important in the case of relatively old bridges with a long service history. An evident change in the load distribution may sometimes lead to unexpected unfavorable effects on the behavior of the bridge after its modernization.

In most considerations, bridge rehabilitation and modernization problems are limited to problems concerning the bridge superstructure only. However, in some situations, the bridge piers and abutments also need to be rehabilitated, modernized or strengthened. For instance, the widening of the bridge deck may demand some changes in the shape of bridge piers and their strengthening. Moreover, the bridge foundations may need to be strengthened. In other words, the whole bridge substructure should also be analyzed and, if necessary, subjected to repair, rehabilitation and strengthening, etc. (cf. Chapter 9).

The main aims of calculations concerning bridge rehabilitation, strengthening or geometrical modernization can be therefore summarized as follows:

(1) Determination of the load-carrying capacity of the existing bridge, including its structural defects and material deterioration, according to current or predicted traffic and other technical or administration requirements — the bridge superstructure and substructure should be analyzed.
(2) Determination of the level of strengthening, if necessary, according to the requirements — the bridge superstructure and substructure should be checked.

(3) Determination of the behavior of the bridge after its rehabilitation, strengthening or geometrical modernization, including safety margin and the new traffic conditions, e.g., in the case of additional lanes on the bridge deck after its modernization by widening.

As mentioned before, the results of the above listed calculations are verified in many cases by field testing (cf. Chapter 4).

However, the calculation problems are only one of several design problems, which can be summarized as follows:

(1) The technical condition of the existing bridge as well as the fundamental properties of its structural materials should be known prior to the design process.
(2) All the technical and functional (mostly traffic) conditions for the bridge after its rehabilitation or modernization including the expected service life of the bridge should be clearly determined.
(3) Making an inventory of the bridge is required in the case of a lack of relevant original documentation.
(4) Comparison between the current standard or other requirements and the original ones should be performed, if possible, to determine the minimum scope of rehabilitation or strengthening of the bridge.
(5) Compatibility of the repair or other new materials to the original structural materials should be a fundamental criterion of the selection of material solutions for bridge rehabilitation (cf. Sec. 5.4).
(6) Familiarity of contractors with products and repair or rehabilitation techniques should be taken into account.
(7) Aesthetical problems should be taken into account, especially regarding old or important bridges (cf. Sec. 5.5).
(8) Cost effectiveness should be considered in particular (cf. Sec. 5.3).
(9) Traffic management for the period of rehabilitation works should be developed.

5.3 Economic Problems

Economic problems of bridge rehabilitation, modernization, etc. are of prime interest due to the great scale of needs on one hand and limited funds on the other. Depending on the country as well as the economic and financial conditions and the road or railway administration systems, these problems are considered using various methods. Therefore, the economics concerning bridge rehabilitation and modernization is presented below in the most general form possible with some exemplifications taken from practice in different countries.

Economic analysis in bridge engineering needs to consider three main components of the costs, namely:

(1) capital costs (total investment costs), i.e., planning, design, total construction costs, etc., denoted below by I,
(2) maintenance costs during the whole expected service life of the bridge, denoted below by E,
(3) benefits arising from the availability and operation of the bridge during the whole expected period of its utilization, denoted below by B.

Therefore, the measure of the efficiency of bridge investments (ε) can be expressed by:

$$\varepsilon = \frac{B}{I + E} \,. \tag{5.2}$$

However, the capital (I) and maintenance costs (E) as well as the benefits (B) occur at different times with different durations. Therefore, to compare the economic efficiency (ε) of different projects or existing bridges as well as to evaluate the costs of different maintenance strategies, it is necessary to bring the values of B, I and E to a common reference time. In general, the beginning of the bridge utilization is assumed to be the reference time. Therefore, Eq. (5.2) can be rewritten in a somewhat different form:

$$\varepsilon_0 = \frac{B_0}{I_0 + E_0} \,, \tag{5.3}$$

where B_0, I_0 and E_0 are the values of B, I, and E, respectively, brought to the above mentioned common reference time.

Assuming that the investment and maintenance expenditures as well as the benefits vary arbitrarily in time, the following equations bringing the unit values (e.g., the year values) of I, E and B to the common reference time can be applied[5.7, 5.8]:

$$i_0(t) = i(t)\exp\left[\left(\frac{t_i - t'}{t_0}\right)\cdot \ln(1+q)\right], \tag{5.4}$$

$$e_0(t) = e(t)\exp\left[\left(\frac{-t''}{t_0}\right)\cdot \ln(1+c)\right], \tag{5.5}$$

$$b_0(t) = b(t)\exp\left[\left(\frac{-t''}{t_0}\right)\cdot \ln(1+a)\right], \tag{5.6}$$

where $i_0(t)$, $e_0(t)$ and $b_0(t)$ are the unit (e.g., one year) investment and maintenance expenditures as well as the unit benefits, respectively, brought to the beginning of the bridge utilization:

$i(t)$, $e(t)$, and $b(t)$ — the unit (e.g., one year) investment and maintenance expenditures as well as the unit benefits, respectively,
t' — time from the beginning of the investment process, mostly from the start of bridge construction,
t_i — time from the beginning of investment process to the start of bridge utilization, mostly the bridge construction time,
t_0 — time unit (e.g., one year),
t'' — time from the beginning of bridge utilization (max $t'' = t_u$, where t_u is the whole predicted service life of the bridge),
q, c, a — discount rates of investment and maintenance costs as well as the benefits, respectively.

Particular values of the discount rates are different depending on the country and its economic system, current financial conditions, financial strategy, etc. According to G. P. Tilly,[5.9] the values of discount rates in the the European countries and the United States vary from 2% to 10% annually, but mostly from 6% to 8% in the developed countries.

The total values of I_0, E_0 and B_0 in Eq. (5.3) can be expressed in the following forms:

$$I_0 = \int_0^{t_i} i_0(t)dt \ , \tag{5.7}$$

$$E_0 = \int_0^{t_u} e_0(t)dt \ , \tag{5.8}$$

$$B_0 = \int_0^{t_u} b_0(t)dt \ , \tag{5.9}$$

where $i_0(t)$, $e_0(t)$ and $b_0(t)$ are expressed by Eqs. (5.3), (5.4) and (5.6), respectively, t_u is the whole predicted service life of the bridge with other notations as before.

In practice, the integration sign ($\int$) in the above equations can be replaced by the summation sign ($\sum$) and the integrands by the functions with linear variation in particular time intervals (e.g., during the year).

Equations (5.3)–(5.9) include all the most important economic and social characteristics such as investment expenditures and their freeze time, maintenance costs and benefits during the whole expected service life of the bridge, etc.

Equation (5.3) indicates that the higher the value of $\varepsilon_{0,}$ the more economically efficient is the bridge. It assists in making decisions concerning selection of projects competing for expenditure.

It should be emphasized that the investment (I_0) and maintenance (E_0) expenditures are relatively easy to predict and their determination or planning are more of a technical and economic nature than of a social one, while prediction of the benefits (B_0) requires an extensive economic and social study including not only the direct transport effects but also some indirect effects occurring in domains other than transport itself.

Direct benefits (B_0') occur in the transport domain and consist mainly of time saving and fuel economy due to more effective road or railway system resulting from bridge operation.

Indirect benefits (B_{01}'') consist mainly of an increase in economic activity and economic values of buildings or recreation grounds in the area where the bridge is located and utilized. These indirect benefits can be classified as calculable and predictable ones. However, other indirect benefits (B_{02}'') resulting from bridge operation also occur, such as an improvement in various social and cultural domains. They are rather difficult to be exactly determined using routine calculation methods but should be taken into account during the decision-making process.

It should be pointed out that in many situations, indirect calculable benefits can be greater than the direct benefits (i.e., $B_{01}'' > B_0'$). However, a more particular analysis of this problem is beyond the scope of this book.

The method of analysis summarized by Eqs. (5.2)–(5.9) can be used for both evaluation of new projects and to make a "ranking list" for bridge rehabilitation and modernization. The only difference is the replacement of investment costs by rehabilitation or modernization costs and the appropriate calculations of the benefits. For instance, it is evident that in many situations, the costs of traffic delays can be many times greater than the costs of bridge works and therefore, the time for bridge rehabilitation or modernization should be minimized whenever possible. As mentioned previously, determination of the benefits requires extensive studies perform in general not only by bridge engineers but also by traffic engineers, town and country planners and long-term planners.

However, the method presented in its general form above can also be applied in a somewhat simpler form as presented by G. P. Tilly[5.9] regarding highway bridges and defined as "whole life costing (WLC)".

WLC method includes the costs of construction, maintenance, traffic management and traffic delays as well as the benefits resulting from the availability and operation of the bridge. The costs are discounted to the present value (PV) according to:

$$PV = \frac{C}{(1+r)^t}\,, \qquad (5.10)$$

where C is cost at current price levels, r is the discount rate and t is the time period expressed in years.

Introducing the calculable benefits at current price levels (B) into Eq. (5.10), the net present value (NPV) can be expressed by:

$$NPV = \sum \frac{B - C}{(1+r)^t} , \tag{5.11}$$

with all notations as before.

It should be noticed that the NPV can be negative when costs exceed benefits. In such a case, construction, rehabilitation or modernization of the bridge is economically not justified. However, it should also be noticed that the discount rate (r) is a dominant element and depending on its value, the NPV can be more or less profitable.

Other new information on economic evaluation of bridge structures can be found, e.g., in Refs. 5.10 and 5.11.

Of course, the analysis of bridge efficiency is highly computerized at present. For instance, the traffic delay costs and its relation to the bridge works can be assessed by the program QUADRO (Queues and Delays at Roadworks) used in the Great Britain.[5.12]

In certain Bridge Management Systems (BMS, cf. Chapter 4), there are special sub-modules focussing on bridge repair, rehabilitation or modernization. One of them being applied in Portugal is presented by F. A. Branco and J. de Brito.[5.13] The decision-making process is performed according to the cost effectiveness index (CEI), indicating "how well the proposed workplan compares to the no-action option". The CEI is expressed by:

$$CEI = \frac{(C_R + C_F - B)_{\text{repair}}}{(C_F - B)_{\text{no-action}}} , \tag{5.12}$$

where C_R is repair (or other action) costs, C_F is the failure costs and B is the benefits.

Equation (5.12) indicates that the bigger the *CEI* is for a particular option, the better an investment is that option. It allows the selection of the most effective options for a given bridge as well as to make a “ranking list” of the needs for the whole bridge stock in the country or its road administrative regions. Moreover, an optimization procedure enables selection of the repair or rehabilitation technique when more than one technique is taken into consideration. Each technique has an associated cost and estimated service life in a special module based on the expert knowledge system.

An example of a cost analysis performed according to F. A. Branco and J. de Brito[5.13] is briefly presented below to explain the fundamental problems of bridge economy and management. Irrespective of its particular nature, this example can be considered as characteristic for analysis performed prior to bridge rehabilitation or modernization.

The example concerns a concrete highway bridge with continuous beam spans with lengths 18 + 21 + 18 m and the slab deck with a total width of 9 m and two lanes. The bridge was opened to traffic in 1987 and its service life is predicted for 50 years (i.e., up to the year 2037). The traffic study has shown that the so-called “area of influence” of the bridge operation on the road length is equal to 12.5 km.

The first step of the analysis was a study of the evolution of functional costs. The rate of evolution of the traffic was predicted based on data collected during the service years of the bridge. It was assumed that due to repair works on the bridge or at rush hour, traffic delay may occur and 20% of the potential traffic volume will choose other roads. An increase in traffic through the bridge was assumed at 15% annually. The benefits included traffic delay, traffic flow detour and heavy traffic detour. The functional failure costs were determined as a reduction of the functionality of the bridge. Therefore, it can be concluded that a benefit is equivalent to a negative functional failure cost. The results of the long-term economic analysis is shown in Fig. 5.3.

It can be noticed that at the end of the predicted service life, the increase in functional failure costs due to delay is so evident that they exceed the global annual benefits. Figure 5.3 also shows that to maximize

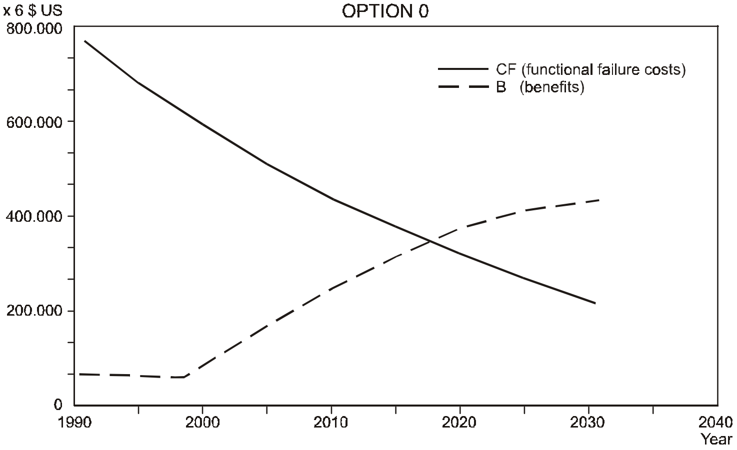

Fig. 5.3 Evolution of functional costs.[5.13]

the net present value (*NPV*) of the bridge (cf. Eq. (5.11)), it should be replaced by a new one when the total annual costs are equal to the total annual benefits (i.e., in 2017), assuming that the cost of opportunity of capital equals the discount rate. In other words, Fig. 5.3 indicates the economically justified functional service life of the bridge when no action is undertaken to increase its traffic capacity.

The second step of the analysis was a consideration concerning the increase of bridge traffic capacity by widening the deck from two lanes to three with the assumption that the extra lane will be used alternatively, according to the rush hours. Five options were studied: no-action option (option 0, Fig. 5.4), the widening of the deck in 1995 (option 1), 2000 (option 2), 2005 (option 3), and 2010 (option 4).

The following additional assumptions for the analysis were made:

- the load-carrying capacity of the bridge in terms of the maximum allowable live load is not affected by the widening of the deck — therefore, the costs of heavy traffic detour are the same for all the options,
- the structural failure costs are affected by the widening of the deck, but they are almost the same for all the options.

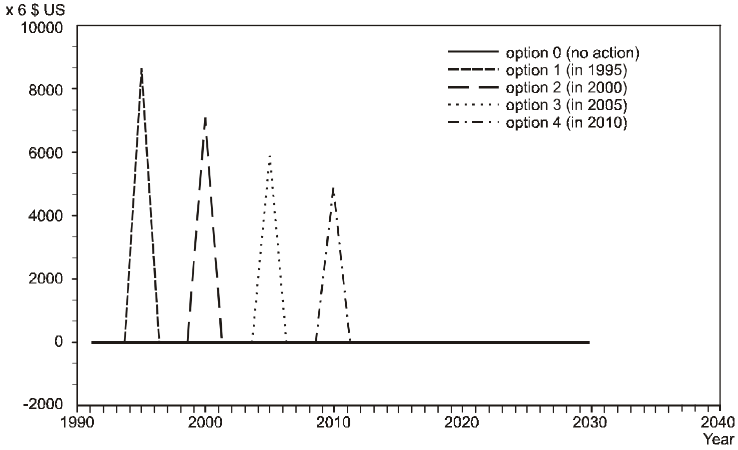

Fig. 5.4 Costs of deck widening.$^{5.13}$

The direct costs of the deck widening were calculated at 1991 present value costs (PV, cf. Eq. (5.10)) as US $60 000. The costs of traffic delay and light traffic detour were taken into consideration. The costs of the deck widening are different depending on the option taken because they occur at different times, as shown in Fig. 5.4.

The influence of the deck widening date on the traffic delay costs (i.e., a part of the functional failure costs) is shown in Fig. 5.5. The peak values correspond to the local traffic delay costs during the construction periods.

The influence of the deck widening date on the detoured light traffic (i.e., other part of the functional failure costs) is shown in Fig. 5.6. The peak values indicate the fraction of the total in excess traffic detoured during the construction periods.

The results of the economic analysis biefly presented above can be summarized numerically by the values of the cost effectiveness index (*CEI*, cf. Eq. (5.12)). These values, corresponding to all the options considered, are as follows$^{5.13}$:

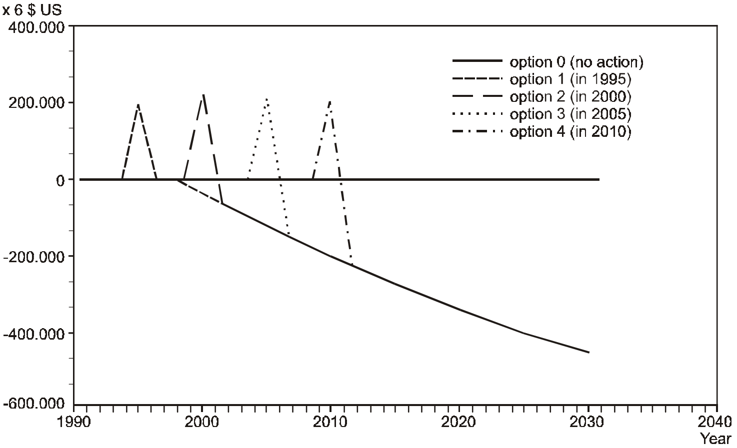

Fig. 5.5 Influence of deck widening on traffic delay.[5.13]

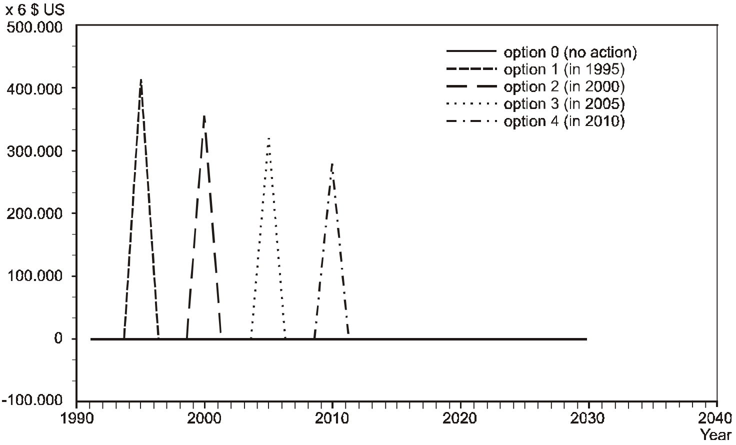

Fig. 5.6 Influence of deck widening on light traffic detour.[5.13]

Option 0 (no-action) → $CEI = 1.0000$
Option 1 (1995) → $CEI = 1.8982$
Option 2 (2000) → $CEI = 1.8942$
Option 3 (2005) → $CEI = 1.8507$
Option 4 (2010) → $CEI = 1.7551$

F. A. Branco and J. de Brito present the following conclusions resulting from the above analysis[5.13]:

- Any of the options that considers widening the deck is preferred to the no-action option;
- The best option is to widen the deck in 1995 or a date between 1995 and 2000 as the first two options have very close results. A more localized analysis would be necessary to reach a definite conclusion;
- Deck widening will significantly increase the functional service life, a situation that is particularly interesting as the end of the bridge structural life will probably not occur in 2017.

However, it should be added that some of the assumptions made in the analysis need to be verified using sensitivity analysis. For instance, the assumed increase in annual traffic (15%) should be verified in particular.

It should also be mentioned that computer technique is an especially useful tool for economic analysis in bridge management, where a great amount of data processing and numerical simulations are necessary. However, the input data should be technically and economically justified in any case. It requires relevant studies prior to the use of computer technique itself. Economic analysis belongs to the most important moduli in the highly computerized bridge management systems (BMS., cf. Chapter 4).

It is obvious that because of their importance, economic problems concerning bridge rehabilitation and modernization demand to be much more widely presented than it is done above; they require a separate book devoted entirely to this subject. However, the limitation of the above presentation to selected problems only serves to be a sufficient base for the readers to read about further, more particular studies. More detailed economic considerations are beyond the scope of this book.

5.4 Material Solutions and Repair Techniques

Material solutions as well as repair techniques are especially important in bridge rehabilitation. There are many available materials or repair systems and associated techniques which can be used. More detailed information on these problems is presented in later chapters, especially in Chapters 6 and 7, which are devoted to the rehabilitation of concrete and steel bridge superstructures. General information regarding the repair of concrete bridges can be found in Ref. 5.14, where the particular extensive references are also included and discussed. Problems concerning the selection of repair materials for concrete structures are discussed by D. Plum,[5.15–5.17] L. Czarnecki and M. Suchan.[5.18] They are also the subject of relevant international and national regulations and standards, e.g., Refs. 5.19–5.21.

However, irrespective of the structural material, i.e., steel, concrete, wood or stone, there are certain general rules required to be observed in the design process concerning bridge rehabilitation and during the rehabilitation works. Therefore, some of the most important problems related to material solutions and repair techniques are briefly presented below in a general form.

To select an appropriate material solution and an adequate repair technique, the following problems should be solved by bridge inspection, "in situ" or laboratory tests (cf. Chapter 4), theoretical analysis, etc., and known prior to the selection. The fundamental problems are presented below as a series of questions:

(a) what are the causes of material deterioration?
(b) what is the nature and type of material deterioration in the bridge structure?
(c) what is the scale of material deterioration — local or global, i.e., occurring in a large part of the structure?
(d) what is the depth of deterioration — only the surface, deeper or throughout the structural elements?
(e) which element of the structure have deteriorated — primary or secondary ones and what is their location in the structure (e.g., external or internal, exposed or not)?
(f) what are the environmental conditions — e.g., normal, moderate or strongly aggressive chemically?
(g) what is the location of material deterioration with respect to internal forces in the structure — e.g., in the tensile or compressive zones?

(h) what is the main purpose of bridge repair or rehabilitation — e.g., restoration of previous load-carrying capacity or its upgrading, assurance of required tightness (in case of concrete bridge), restoration of both required load-carrying capacity and tightness?
(i) what is important in the repair — aesthetic only or affecting the structural behavior?

Answers to all these questions are the basis for the selection of an appropriate material solution.

Of course, the particular names of repair products or material systems are not given in this section of the book nor in the following chapters — specification or promotion of particular material solutions is not the subject of the book. It is necessary, instead, to present certain fundamental criteria and conditions, which should be fulfilled by the repair materials.

In the case of steel bridge, repair problems are more concerned with the selection of repair techniques adequate to the given situation than the repair material itself (cf. Chapter 7). Repair materials for steel bridges are mostly steel and steel products (e.g., cables) or, in some situations, composite materials and products such as strips or sheets (cf. also Chapter 7). However, the properties of steel as repairing material should conform to structural steel. This requirement concerns mainly weldability of both steels and avoidance of corrosion cell when the steels are not in electrochemical conformity.

In the case of concrete bridge, repair problems are much more complex and concern both selection of repair materials and repair techniques (cf. Chapter 6). Because of the different natures and types of material and structural deterioration (cf. Chapter 3) and the necessity to repair or protect two different materials, i.e., concrete and reinforcing or prestressed steel, there are a great variety of material and technique solutions. They are presented in Chapter 6. The general requirements concerning the material to repair concrete are presented below.

It should be mentioned that the requirements have varied in time. During a relatively long period, the similarity of the constituent materials in the repairing material and the material to be repaired (i.e., "concrete to concrete" repair) has been considered a fundamental condition.[5.18, 5.23] It has eliminated the use of new materials. However, the principal rule for the use of repair materials has changed during recent years.[5.18, 5.24] This rule can be formulated as follows: the repairing material and the material to be repaired should be physically and chemically compatible. In other words, a good interaction between these two materials should be assured. This good interaction can be defined as the material ability to conserve stresses or strains within allowable limits under required service conditions and in the desired period of time.[5.18]

More general requirements for the repairing materials can be classified into two main groups as follows[5.18]:

(a) basic requirements, which should be fulfilled by any repairing material as a necessary condition, but not always a sufficient one,
(b) additional requirements, which depend on the type of repair and environment and together with the basic requirements make a sufficient condition.

The above requirements are presented in particular in Chapter 6. However, to explain the problem, it should be indicated that the bond, measured usually by means of the "pull off" method, is normally a decisive factor influencing interaction between the repairing material and the material to be repaired. Therefore, the bond belongs to the basic requirements (i.e., to group (a)), like shrinkage, which should be low. Some other material properties, such as compressive strength, modulus of elasticity, permeability, diffusion coefficient for CO_2, Cl^- and water vapor as well as coefficient of thermal expansion (α_t), belong to the additional requirements (i.e., to group (b)).

It should be emphasized that when the repairing material and material to be repaired have different values of the coefficient α_t, the factor, which may influence the behavior of the repaired system, is not the coefficient value itself, but the product ($\alpha_t \cdot E$), where E is the modulus of elasticity. The difference between ($\alpha_t \cdot E$) for these two materials influences the stress in their contact layer. This problem should be taken into account in bridge repair due to the fact that the bridges are exposed both to the variation in ambient temperature and solar radiation. For this reason, some practical guides for the use of repair material with the coefficient of thermal expansion and modulus of elasticity as close as possible to the existing concrete are recommended.[5.22]

Finally, it should be mentioned that the selection of appropriate material for bridge repair and rehabilitation is difficult and requires a lot of engineering experience and even “technical intuition”. The standardization of this problem is at its initial stage, e.g., Ref. 5.25 and does not sufficiently include the specificity of bridge structures.

Selection of repair techniques for concrete bridges is closely associated with the type of repairing material and scale, type, shape (e.g., shallow or deep repairs) and location of the material and structural deterioration. There are many techniques for use — from hand methods (e.g., hand-applied mortar) to highly mechanized ones (e.g., pneumatically applied mortar or pumping concrete), including special robots.

One of the basic selection criteria is the easy and safe application of the repair technique. Moreover, it should be taken into account that the bridge repairs are usually performed in extremely difficult conditions concerning both accessibility to the deteriorated structural elements and the works under normal traffic.

More detailed information on repair techniques applied to the rehabilitation of concrete bridges is given in Chapter 6.

5.5 Maintenance Problems

Maintenance problems should also be taken into consideration in the decision-making process concerning bridge rehabilitation and modernization. These problems are presented below in a general form, irrespective of the structural system and structural material of the bridge. More detailed aspects are discussed in the following chapters.

A specificity of the considerations can be characterized by the following main problems needed to be solved:

(a) A relation between the costs of repair materials and repair techiques used for bridge rehabilitation and the maintenance costs after rehabilitation requires special analysis and the use of optimization procedures. In general, an increase in material and labor costs leads to a decrease in maintenance cost during bridge service after rehabilitation. Therefore, the required bridge durability and prediction of its service life are necessary for making optimum decision concerning selection of material and technique solutions.

(b) Bridge rehabilitation cannot be limited to the structure itself or their individual members. It should also include repair or replacement of bridge equipment elements, such as drainage system, expansion joints, pavement, insulation, etc. It is commonly known that deterioration of the structure results mostly from the poor condition and low quality of these elements or their insufficient routine maintenance and conservation. The modern bridge equipment elements are of high quality and durability, but their use evidently increases the costs of bridge rehabilitation. In spite of it, replacement of the "old" equipment elements instead of their repair is in general technically and economically justified by an evident improvement in bridge durability. However, this problem requires individual analysis in any situation.

(c) In the case when rehabilitation of the bridge is associated with its modernization, e.g., by the deck widening, the maintenance problems should also be analyzed. The existing deck may be entirely replaced by a new one or the "old" deck can remain (entirely or partially), and the new parts of the deck may be joined to the "old" one. In both these situations, the maintenance conditions can be different to those before modernization; this is mainly due to modernization or replacement of the drainage system, expansion joints, insulation, pavement, etc. Therefore, this problem also needs to be solved.

(d) The inspection and routine maintenance of the bridge should be easier to carry out than before its rehabilitation. It should be taken into account during the design process. Appropriate equipment (e.g., inspection platforms or scaffoldings, spiders, ladders, etc.) enabling access to the structural members to check their technical condition should be installed.

(e) For maintenance purposes as well as to enable future replacement of bridge bearings or other operations, slight changes in the original structure can be recommended during bridge rehabilitation, e.g., special cavities in the heads of the bridge piers for the installation of jacks for lifting up the bridge superstructure to replace the bridge bearings.

The above maintenance problems connected with bridge rehabilitation and modernization are selected only to exemplify a great variety of engineering tasks and to indicate that any problem should not be ignored.

5.6 Aesthetic Problems

Aesthetic problems should also be deeply analyzed prior to bridge rehabilitation itself. The rehabilitation is, in many situations, associated with the evident change in the original structural form of the bridge (e.g., by providing structural continuity over the piers) and the change in its color. The change in color may concern both structural elements (e.g., main girders in steel bridges) and bridge equipment elements (e.g., balustrades). The bridge color is a very important factor affecting both the appearance of the structure itself and the aesthetic value of the bridge surroundings.

Aesthetics is especially important when the bridge is geometrically modernized by the widening of its deck. This operation strongly influences the bridge appearance. Depending on the structural system, the deck widening can require additional girders or beams. It may demand the widening or strengthening of the bridge piers. Therefore, the original shape and the geometrical proportions of the structure can be distorted.

Similarly, in some situations, the superstructure can be lifted to increase the clearance under the bridge. It requires some changes in the geometry of bridge piers, which also affects the general bridge silhouette.

Some other problems concerning the aesthetic aspects of bridge geometrical modernization are presented in Chapters 6, 7 and 10.

Aesthetic problems also occur in cases of bridge strengthening, especially when external prestressing tendons (cf. Chapter 6) are used. Because of aesthetical requirements, the tendons are located between the girders or beams and not visible within their depth in the bridge elevation.

All the above examples indicate that bridge aesthetics belongs to the important problems concerning bridge rehabilitation, strengthening and geometrical modernization and also affect the selection of structural and material solutions.

However, aesthetic problems are particularly important when bridges of considerable architectural or historical values need to be rehabilitated or modernized. Depending on its individual value and traffic functionality, the historical bridge can be restored, modernized or replaced by a new structure. One of the options is closing the bridge to normal traffic and subsequent utilization of the structure as a specific technical museum (cf. Sec 5.1).

When a historical bridge with an architectural heritage is restored without any changes in its architectural form, the repair materials should be selected in accordance with the requirements concerning preservation of monuments and historical buildings. These requirements are beyond the scope of this book. More information on the restoration of historical buildings can be found, e.g., in Ref. 5.26.

When a bridge of considerable historical value is geometrically modernized (e.g., by the deck widening), every planned change in its architectural form should be analyzed to minimize the loss of historical and aesthetic merits of the structure.

As mentioned above, some other aesthetic aspects of bridge repair, strengthening, and modernization are presented and discussed in more detail in the next chapters.

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