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## Planning of Major Fixed Links

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## 4.1 Introduction

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### Characteristics of Fixed Links

Within the infrastructure of land transportation, fixed links are defined as permanent structures across large stretches of water allowing for uninterrupted passage of highway and/or railway traffic with adequate safety, efficiency, and comfort.

Traffic services are often provided by ferries before a fixed link is established. Normally, a fixed link offers shorter traveling times and higher traffic capacities than the ferry services. The establishment of a fixed link may therefore have a strong positive impact on the industrial and economic development of the areas to be served by the link. This together with an increased reliability in connection with climatic conditions are the major reasons for considering the implementation of a fixed link.

The waters to be passed by the links are often navigable; the link structures may present obstacles to the vessel traffic and are thus subject to the risk of impact from vessels. If the vessel traffic is important, the link traffic may be better separated from the crossing vessel traffic for general traffic safety. The water flow is often influenced by the link structures and this may affect the environment both near and far from the site. Furthermore, the water stretches and areas to be passed are part of beautiful territories forming important habitats for wildlife fauna and flora. The protection and preservation of the environment will therefore often be a major issue in the political discussions prior to the establishment of the links. These aspects have to be realized and considered in the very beginning of the planning process.

**TABLE 4.1** Major Fixed Links Opened Since 1988

Name of Link	Total Length and Types of Structures	Status Early 1998	Traffic Mode
Confederation Bridge, Canada	12.9 km, high-level concrete box girder bridge	Open to traffic 1997	Highway traffic
Vasco da Gama Bridge, Portugal	12.3 km, viaducts and high-level cable-stayed bridge	Open to traffic 1998	Highway traffic
Second Severn Bridge, Great Britain	5.1 km, viaducts and high-level cable-stayed bridge	Open to traffic 1996	Highway traffic
Honshu–Shikoku Connection, Japan			
• Kojima–Sakaide Route	37.3 km, a o high-level suspension bridges	Open to traffic 1988	Highway and railway
• Kobe–Naruto Route	89.6 km, a o high-level suspension bridges	South part open 1998	Highway traffic
• Onomichi–Imabari Route	59.4 km, a o high-level suspension bridges	Under construction	Highway traffic
Lantau Fixed Crossing, Hong Kong	3.4 km High-level suspension bridge	Open to traffic 1997	Highway and railway
• Tsing Ma Bridge	High level cable stayed bridge	Open to traffic 1997	Highway and railway
• Kap Shui Mun Bridge			
Boca Tigris Bridge, China	4.6 km, high-level suspension bridge	Open to traffic 1997	Highway traffic
Great Belt link, Denmark	17.5 km		
• West Bridge	6.6 km, low-level concrete box girder bridge	Open to traffic 1997	Highway and railway
• East Bridge	6.8 km, high-level suspension bridge	Open to traffic 1998	Highway traffic
• East Railway Tunnel	8.0 km, bored tunnel, two tubes	Open to traffic 1997	Railway traffic
Øresund link, Sweden–Denmark	16 km, immersed tunnel, artificial island, high-level cable-stayed bridge, viaducts	Under construction	Highway and railway
Rion–Antirion Bridge, Gulf of Corinth, Greece	2.9 km, high-level cable-stayed bridge, viaducts	Construction started in 1998	Highway traffic
Channel Tunnel, Great Britain–France	50.5 km, bored tunnel, three tubes	Open to traffic 1994	Railway with car and lorry shuttle
Trans-Tokyo Bay Crossing, Japan	15.1 km, bored tunnel, artificial islands, high- and low-level steel box girder bridges	Open to traffic 1997	Highway traffic

Generally, the term *fixed link* is associated with highway and/or railway sections of considerable length and a fixed link may comprise a combination of different civil engineering structures such as tunnels, artificial islands, causeways, and different types of bridges. Selected examples of major fixed links opened or are under construction since 1988 are listed in [Table 4.1](#).

## Planning Activities for Major Fixed Links

Major fixed links represent important investments for the society and may have considerable influence on the development potential of the areas they serve.

The political discussions about the decision to design a fixed link may be extended over decades or even centuries. In this period planning activities on a society level are necessary to demonstrate the need for the fixed link and to determine positive and negative effects of the implementation. These early planning considerations are outside the scope of this chapter, but the outcome of the early planning activities may highly influence the tasks in the later planning phases after the final decision is made.

In the early planning phases, basic principles and criteria are dealt with, such as

- Ownership and financing
- Approximate location
- Expected service lifetime
- Necessary traffic capacity
- Considerations for other forms of traffic like vessel traffic and air traffic
- Principles for environmental evaluation
- Risk policy
- International conventions

Section 4.2 will explain the later planning phases by describing major steps in project development with emphasis on the consideration of all relevant aspects. The focus will be on the technical and civil engineering aspects of bridges as fixed links, but most of the methods and principles described can be applied to other types of link structures. In the case of complex fixed link arrangements (comprising more than one type of structure), some of these structures may be alternative solutions. Several combined solutions are therefore studied and for each combination it is normally necessary to perform the planning for the entire link as a whole.

The elements of the project basis for a major fixed link are further detailed in Section 4.3, and examples of major fixed links recently built, under construction, or in the planning stage in the Scandinavian area are described in Section 4.4.

The chapter does not treat aesthetic and environmental issues individually, but assumes that all alternatives are evaluated according to the same principles. Public approval processes are beyond the aim of this chapter; readers are referred to References [1–3].

Fixed links are unique in size and cost, and the political environment differs from project to project. It is thus not possible to provide a recipe for planning major fixed links. The present chapter describes some of the elements, which the authors believe are important in the complex, multidisciplinary planning process of all fixed links.

Many important fixed links still remain to be planned and built. One of the more spectacular ones is the Gibraltar link between Africa and Europe. [Figure 4.1](#) shows an artist's impression of the bridge pylons for the planned Gibraltar link. Examples of other future links are the Messina Strait crossing in Italy, the Mallaca Strait crossing between Malaysia and Indonesia, and the Río de la Plata Bridge connecting Argentina and Uruguay.

## 4.2 Project Development

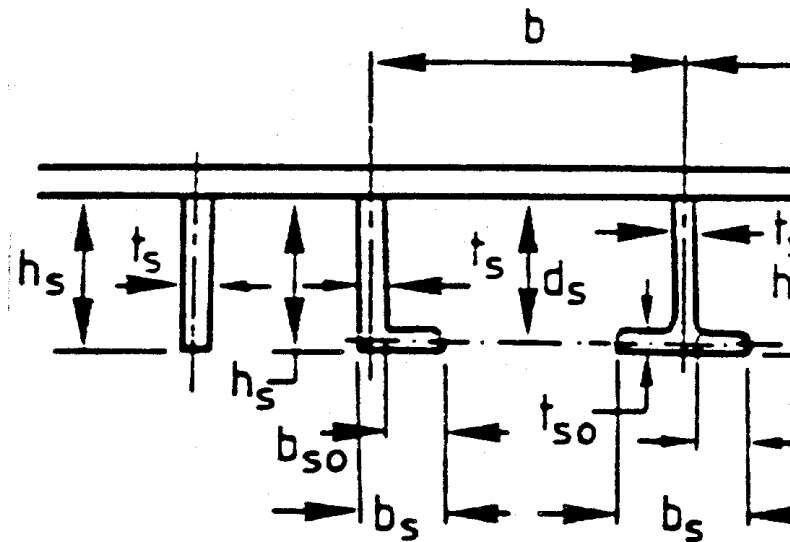
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### 4.2.1 Initial Studies

The first step in project development consists of a review of all information relevant to the link and includes an investigation of the most likely and feasible technical solutions for the structures.

The transportation mode, highway and railway traffic, and the amount of traffic is determined based on a traffic estimate. The prognosis of traffic is often associated with considerable uncertainty since fixed links will not only satisfy the existing demands but may also create new demands due to the increased quality of the transport. For railway traffic, it has to be decided whether a railway line will accommodate one or two tracks. Similarly, the highway traffic can either be transported on shuttle trains or the bridge can be accommodated with a carriageway designed to a variety of standards, the main characteristics being the number of lanes.

The decision on the expected traffic demands and the associated traffic solution models is often based on a mix of technical, economic, socioeconomic, and political parameters. The decision may be confirmed at later stages of the planning when more information is available.



**FIGURE 4.1** Artist's impression of 465-m-high pylon on 300 m water for planned Gibraltar link with 3,500 m spans. (Courtesy of Dissing +Weitling, Architects, Denmark.)

A *fixed link concept study* will review alignment possibilities and define an appropriate corridor for further studies. It will consider the onshore interchanges for the anticipated traffic modes and identify potential conflict areas. It describes all feasible arrangements for the structures from coast to coast, and reviews the requirement for special onshore structures. Finally, the study defines the concepts to be investigated in greater depth in subsequent phases.

An *environmental condition study* aims to identify potential effects the structures may have on the environment and to review the legal environmental framework. It also identifies important conflict areas and describes the project study area. It will review the available information on the marine and onshore environment and define the need for additional investigations.

A *technical site condition study* will address the geological, the foundation, the navigation, the climatic, and the hydraulic conditions. It will review the topographic situation and define additional studies or investigations for the following project phase.

A *preliminary design basis study* will review the statutory requirements, codes, and standards and identify the need for relevant safety and durability requirements.

Finally, a *preliminary costing basis study* will define the cost estimation technique and provide first preliminary cost estimates.

Considering the results of these studies a comprehensive investigation program for the next project step — the conceptual study — will be defined.

## 4.2.2 Conceptual Study

The conceptual study is an iterative process, where all the aspects likely to influence the project should be considered, weighted, and clarified to achieve the most suitable solution for the intended purpose and location. These aspects are cost, construction, structural, navigational, environmental, aesthetic, risk, geological, vessel collision, wind, and earthquake.

After an interim selection of various alternatives, conceptual studies are undertaken for each selected alternative solution. Preliminary site investigations like subsoil investigations in the defined alignment corridor, wind, earthquake, and vessel traffic investigations will be carried out simultaneously with the conceptual studies.

The conceptual study comprises development of a project basis, including

- Defining functional requirements
- Reviewing and defining the navigational aspects
- Establishing risk policy and procedures for risk management
- Specifying design basis including structure-specific requirements
- Developing the costing basis

Each of the selected solutions will be developed in a conceptual design and described through drawings and descriptions. The conceptual design will comply with the project basis and further consider:

- Preliminary site investigations
- Structural aspects
- Architectural aspects
- Environmental aspects
- Mechanical and electrical installations and utilities
- Definitions and constraints for operation and maintenance
- Cost aspects
- Major construction stages

Practically, it is not possible to satisfy all the above requirements, but effort should be made to achieve a balanced solution. The conceptual study phase is concluded by a comparison analysis with predeterminant weighting of parameters, which provides the technical ranking of all alternative solutions.

### **4.2.3 Project Selection and Procurement Strategy**

#### **Project Selection**

By using the results from the technical ranking of the solutions, the basis for a project selection has to be established by the owner organization. This requires information from other investigations carried out in parallel with the technical studies that cover:

- Environmental impact assessment including hydraulic studies;
- Traffic demand studies including possible tariff structures;
- Layout, cost, and requirements for connections to the existing network outside the study areas;
- Definition of the project implementation and the tendering procedure.

The information obtained from the above studies may be used as input into a cost–benefit model of the anticipated solutions. These final results usually provide the basis to make a decision that will best consider local and global political viewpoints. Public hearings may be necessary in addition to the investigations. The result of this process is the selection of the solution of choice.

#### **Procurement Strategy**

The optimum procurement method should ensure that the work and activities are distributed on and executed by the most qualified party (owner, consultant, contractor) at all phases, to meet the required quality level, at the lowest overall cost. The procurement strategy should clarify tendering procedures with commercial and legal regulations for the region. In the following, three main

contracting concepts in the definition of the procurement strategy for a fixed link project are presented.

## Contracting Concepts

The three main concepts are as follows:

- *Separate Design and Construction (SDC)* is a concept in which the construction contract documents are prepared by the owner, often assisted by an engineering consulting team, and the construction is performed by a contractor.
- *Design-Build (DB)* is a concept in which both engineering design and construction responsibilities are assigned to a single entity, most often the contractor.
- *Design-Built-Operate and Transfer (BOT)* is a concept in which the financing, design, construction, and operation are assigned to a concessionaire. After an agreed number of years of operation, the link is transferred to the owner. The BOT is not described further because it uses the same design and construction procedure as the DB.
- The *SDC* concept requires that the owner and the consultant participate actively during all phases to influence and control the quality and performance capability of the completed facility. The main differences between the various forms of the SDC are the degree of detailing at the tender stage and whether alternatives will be permitted. Completing the detailed design prior to inviting tenders is good if the strategy is to obtain lump-sum bids in full compliance with the owner's conditions.

Tendering based on a partial design — often 60 to 70% — represents a compromise between initial design costs and definitions of the owner's requirements to serve as a reference for alternative tenders. This procurement strategy has been applied for large construction works from the 1970s. Advantages are that the early start of the construction work can be achieved while completing the design work and that innovative ideas may be developed between the owner, contractor and the consultant, and incorporated in the design. The procedure usually allows contractors to submit alternatives in which case the tender design serves the important purpose of outlining the required quality standards. A disadvantage, however, is the risk for later claims due to the fact that the final design is made after awarding the construction contract. The more aggressive contracting environment and the development of international tender rules have made it desirable to procure on a completely fixed basis.

The *DB* concept assigns a high degree of autonomy to the contractor, and, as a consequence, the owner's direct influence on the quality and performance of the completed facility is reduced. To ensure that the contractor delivers a project that meets the expectations of the owner, it is necessary to specify these in the tender documents. Aesthetic, functional, maintenance, durability, and other technical standards and requirements should be defined. Also legal, environmental, financial, time, interface, and other more or less transparent constraints to the contractor's freedom of performance should be described in the tender documents in order to ensure comparable solutions and prices. Substantial requirements to the contractor's quality assurance system are essential in combination with close follow-up by the owner.

Tenders for major bridges may be difficult to evaluate if they are based on substandard and marginal designs or on radical and unusual designs. The owner then has the dilemma of either rejecting a low tender or accepting it and paying high additional costs for subsequent upgrading.

## Contract Packaging

The total bridge project can be divided into reasonable contract parts:

- Vertical separation (e.g., main bridge, approach bridges, viaducts, and interchanges);
- Horizontal separation (e.g., substructure and superstructure);
- Disciplinary separation (e.g., concrete and steel works).

The application of these general principles depends on the specific situation of each project. Furthermore, the achievement of the intended quality level, together with contract sizes allowing for competitive bidding, should be considered in the final choice. Definition and control of interfaces between the different contractors is an important task for the owner's organization.

#### **4.2.4 Tender Design**

The main purpose of a tender design or a bid design is to describe the complexity of the structure and to determine the construction quantities, allowing the contractors to prepare a bid for the construction work. The goal for a tender design is as low cost as possible within the given framework. This is normally identical to the lowest quantities and/or the most suitable method. It is essential that the project basis be updated and completed prior to the commencement of the tender design. This will minimize the risk of contract disputes.

It is vital that a common understanding between consultant and owner is achieved. Assumptions regarding the physical conditions of the site are important, especially subsoil, wind, and earthquake conditions. Awareness that these factors might have a significant impact on the design and thereby on the quantities and complexity is important. The subsoil conditions for the most important structures should always be determined prior to the tender design to minimize the uncertainty.

Determination of the quantities is also necessary. For instance, if splice lengths in the reinforcement are included, if holes or cutouts in the structure are included, what material strengths are assumed. There must be stipulated an estimate of the expected variation of quantities (global or local quantities).

The structures in the tender design shall be constructible. In an SDC contract, the tender design should be based on safe and well-established production and erection procedures. In the case of DB, the tender design is carried out in close cooperation between the contractor and the consultant. This assures that the design accommodates the contractor's methods and the available equipment.

The tender design is often carried out within a short period of time. It should focus on elements with large cost impact and on elements with large uncertainties in order to arrive as closely as possible at the actual quantities and to describe the complexity of the structure efficiently from a costing point of view. A tender design comprises layout drawings of the main structural elements, detailed drawings of typical details with a high degree of repetition, typical reinforcement arrangement, and material distribution.

Aesthetics are normally treated during the tender design. It is important that extreme event loads such as vessel collision, train derailment, cable rupture, earthquake, and ice impact should be considered in the tender design phase as they often govern the design. Durability, operation, and maintenance aspects should be considered in the tender design. Experience from operation and maintenance of similar bridges allows a proper service life design to be carried out. It is at the early design stages that the construction methods should be chosen which have a significant effect on further operation and maintenance costs.

It is not unusual that a tender design is prepared for more than one solution to obtain the optimal solution. It could, for instance, be two solutions with different materials (concrete and steel) as for the Storebælt East Bridge. It could also be two solutions with traffic arranged differently (one level or two levels) as for the Øresund link. Different structural layouts as cable stayed and suspension bridge could be relevant to investigate under certain conditions. After the designs are prepared to a certain level, a selection can be carried out based on a preliminary pricing, and one or more solutions are brought all the way to tender.

Tender documents to follow the drawings should be prepared. The tender documents comprise bill of quantities, special specifications, and the like.



#### 4.2.5 Tender Evaluation

The objective of tender evaluation is to select the overall most advantageous tender including capitalized owner's risk and cost for operation and maintenance. A basis should be established via a rating system where all tenders become directly comparable. The rating system is predefined by the owner, and should be part of the tender documents.

The tender evaluation activities can be split up in phases:

1. Preparation
2. Compilation and checking of tenders
3. Evaluation of tenders
4. Preparation for contract negotiations
5. Negotiation and award of contract

The *preparation* phase covers activities up to the receipt of tenders. The main activities are as follows:

- Establish the owner's risk for each of the tendered projects, using the owner's cost estimate;
- Define tender opening procedures and tender opening committee;
- Quantify the differences in present value due to function, operation, maintenance, and owner's risk for each of the tendered projects, using the owner's cost estimate.

After receipt of tenders, a summary report, which collects the information supplied in the different tenders into a single summarizing document and presents a recommendation of tenders for detailed review, as a result of *compilation and checking of tenders*, should be prepared. Typical activities are as follows:

- Check completeness of compliance of all tenders, including arithmetical correctness and errors or omissions;
- Identify possible qualifications and reservations;
- Identify parts of tenders where clarification is needed, or more detailed examination required;
- Prepare a preliminary list of questions for clarification by the tenderers;
- Review compliance with requirements for alternative designs;
- Upgrade alternative tender design and pricing to the design basis requirements for tender design.

The *evaluation of tenders* comprises the following:

- Provide initial questionnaires for tender clarification to tenderers, arrange clarification meetings, and request tenderers' written clarification answers;
- Adjust tender prices to a comparable basis taking account of revised quantities due to modified tender design effects of combined tenders, alternatives, options, reservations, and differences in present value;
- Appraise the financial components of the tenders;
- Assess owner's risk;
- Review technical issues of alternatives and their effect on interfaces;
- Review the proposed tender time schedule;
- Evaluate proposed subcontractors, suppliers, consultants, testing institutes, etc.
- Review method statements and similar information;
- Establish list of total project cost.

The assessment of owner's risk concerns exceeding budgets and time limits. An evaluation of the split of financial consequences between contractor and owner should be carried out.

*Preparation for contract negotiations* should be performed, allowing all aspects for the actual project type to be taken into account. Typical activities are as follows:

- Modify tender design to take current status of the project development into account to establish an accurate contract basis;
- Modify tender design to accommodate alternatives;
- Coordinate with the third parties regarding contractual interfaces;
- Coordinate with interfacing authorities;
- Establish strategies and recommendations for contract negotiations.

The probable extent and nature of the negotiations will become apparent from the tender evaluation. Typical activities during *negotiations and award of contract* are as follows:

- Prepare draft contract documents;
- Clarify technical, financial, and legal matters;
- Finalize contract documents.

## 4.2.6 Detailed Design

The detailed design is either carried out before (SDC contracts) or after signing of the construction contract (DB contracts). In the case the detailed design is carried out in parallel with the construction work, the completion of the detailed design should be planned and coordinated with the execution. A detailed planning of the design work is required when the parts of the structure, typically the foundation structures, need to be designed and constructed before the completion of the design of the entire structure. Design of temporary works is normally conducted in-house by the contractor, whereas the design of the permanent works is carried out by the consultant.

The purpose of the detailed design is to prepare drawings for construction in accordance with various requirements and specifications. Detailed design drawings define all measures and material qualities for the structure. Shop drawings for steel works are generally prepared by the steel fabricator. Detailed reinforcement arrangements and bar schedules are either prepared by the contractor or the consultant. It is important that the consultant prescribes the tolerance requirements of the design.

The detailed design should consider the serviceability limit state (deflection and comfort), the ultimate limit state (strength and stability), and the extreme event limit state (collapse of the structure). To ensure the adequacy of the design, substantial analyses, including three-dimensional global finite-element analyses, local finite-element analyses, and nonlinear analyses both in geometry and materials, should be carried out. Dynamic calculations, typically response spectrum analyses, are usually performed to determine the response from wind. The dynamic amplifications of traffic loads and cable rupture are determined by a time-history analysis, which is also frequently used for vessel collision and earthquake analyses.

For large cable-supported bridges, wind tunnel testing is conducted as part of the detailed design. Preliminary wind tunnel testing is often carried out in the tender design phase to investigate the aerodynamic stability of the structure. Other tests, such as scour protection and fatigue tests can be carried out to ensure design satisfactions. Detailed subsoil investigations for all foundation locations are carried out prior to, or in parallel with, the detailed design.

The operation and maintenance (O&M) objectives should be implemented in the detailed design in a way which:

- Gives an overall cost-effective operation and maintenance;
- Causes a minimum of traffic restrictions due to O&M works;
- Provides optimal personnel safety;
- Protects the environment;
- Allows for an easy documentation of maintenance needs and results.

In addition, the contractor should provide a forecast schedule for the replacement of major equipment during the lifetime of the bridge.

#### **4.2.7 Follow-Up during Construction**

During the construction period the consultant monitors the construction work to verify that it is performed in accordance with the intentions of the design. This design follow-up, or general supervision, is an activity which is carried out in cooperation with (and within the framework of) the owner's supervision organization.

The general supervision activities include review of the contractor's quality assurance manuals, method statements, work procedures, work instructions, and design of temporary structures, as well as proper inspections on the construction site during important construction activities. The quality of workmanship and materials is verified by spot-checking the contractor's quality control documentation.

When the work results in mistakes or nonconformances, the general supervision team evaluates the contractor's proposals for rectification or evaluates whether or not the structural element in question can be used as built, without any modifications. The general supervision team also evaluates proposals for changes to the design submitted by the contractor and issues recommendations on approval of such proposals.

The duties of the general supervision team also include preparation of technical supervision plans, which are manuals used by the supervision organization as a basis for the technical supervision of the construction work. These manuals should be based on inputs from the consultants and experienced engineers to avoid mistakes during the construction work.

The general supervision team monitors the performance of the supervision organization and receives feedback on experience gained by the supervision organization, as in some cases it may be found necessary and advantageous to adjust the design of the project to suit the contractor's actual performance.

The general supervision team provides advice on the necessity for expert assistance, special testing of materials, and special investigations. The general supervision team evaluates the results of such activities and issues recommendations to the owner. Special testing institutes are often involved in the third-party controls which normally are performed as spot checks only. Examples are nondestructive testing of welds, mechanical and chemical analyses of steel materials, and testing of concrete constituents such as cement, aggregates, and admixtures at official laboratories.

The general supervision team assists the supervision organization with the final inspection of the works prior to the contractor's handing over of the works. The general supervision team assists the consultant with the preparation of operation and maintenance manuals and procedures for inspections and maintenance during the operation phase. Some of these instructions are based on detailed manuals prepared by the contractor's suppliers. This can apply to bearings, expansion joints, electrical installations, or special equipment such as dehumidification systems or buffers. Preparation of these manuals by the suppliers is part of their contractual obligations, and the manuals should be prepared in the required language of the country where the project is situated.

### **4.3 Project Basis**

#### **4.3.1 Introduction**

The project basis is all the information and requirements that are decisive in the planning and design of a fixed link. The project basis is developed simultaneously with the early design activities, and it is important to have the owner's main requirements defined as early as possible, and to be precise about what types of link solutions are to be included.

### 4.3.2 Geometric Requirements

Most geometric requirements for the fixed links stem from the operational requirements of traffic and all the important installations. However, geometric requirements may also be necessary to mitigate accidents and to provide the needed space for safety and emergency situations. Geometric considerations should be addressed in the risk analyses.

### 4.3.3 Structural Requirements

#### Design Basis

A main purpose of a design basis is to provide a set of requirements to ensure an adequate structural layout, safety, and performance of the load-bearing structures and installations for the intended use.

#### Structural Design Codes

The structures must resist load effects from self-weight and a variety of external loads and environmental phenomena (climate and degradation effects). To obtain an adequately uniform level of structural safety, the statistical nature of the generating phenomena as well as the structural capacity should be considered. A rational approach is to adapt probabilistic methods, but these are generally inefficient for standard design situations, and consequently it is recommended that a format as used in codes of practice be applied. These codes are calibrated to achieve a uniform level of structural safety for ordinary loading situations, and probabilistic methods can subsequently be used to calibrate the safety factors for loads and/or design situations that are not covered by the codes of practice.

The safety level — expressed as formal probability of failure or exceeding of limit state — is of the order  $10^{-6}$  to  $10^{-7}$ /year for ultimate limit states for important structures in major links.

### 4.3.4 Environmental Requirements

Fixed links crossing environmentally sensitive water stretches need to be developed with due attention to environmental requirements. Environmental strategies should be directed toward modification of the structural design to reduce any impact and to consider compensation or mitigation for unavoidable impacts. Guidelines for environmental considerations in the structural layout and detailing and in the construction planning are developed by a consultant, and these should typically address the following areas:

- Geometry of structures affecting the hydraulic situation;
- Space occupied by bridge structures, ramps and depot areas;
- Amount and character of excavated soils;
- Amount of external resources (raw materials winning);
- Methodology of earth works (dredging and related spill).

Consequences of the environmental requirements should be considered in the various project phases. Typical examples for possible improvements are selection of spans as large as possible or reasonable, shaping of the underwater part of foundations to reduce their blocking effect, orientation of structures parallel to the prevailing current direction, minimizing and streamlining of protection structures, reduction of embankment length, optimal layout of depot areas close to the shorelines, and reuse of excavated material.

The process should be started at the very early planning stages and continued until the link is completed and the impact on the environment should be monitored and assessed.

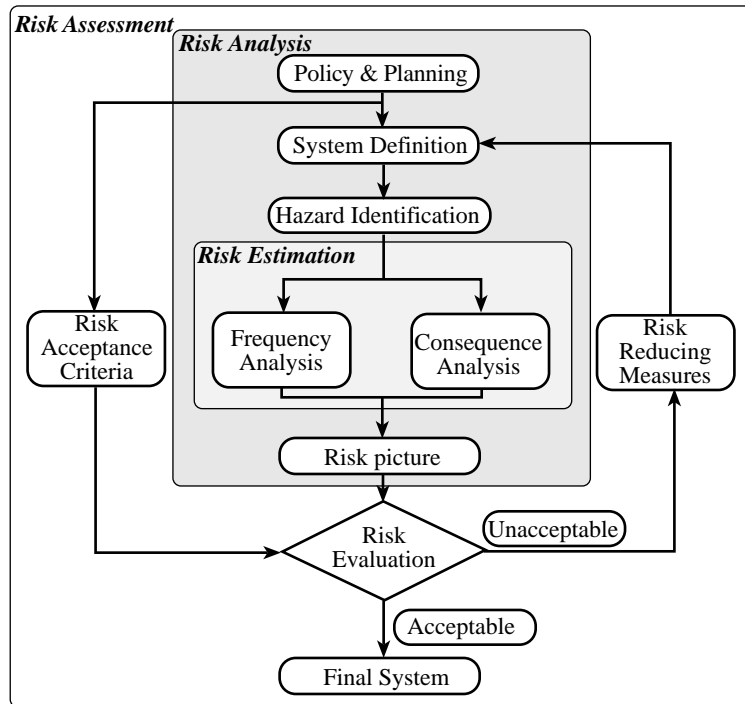


FIGURE 4.2 Risk management components.

### 4.3.5 Risk Requirements

#### Types of Risk

Risk studies and risk management have gained a widespread application within the planning, design, and construction of fixed links. Risks are inherent in major transportation links, and therefore it is important for the owner and society that risks are identified and included in the project basis together with the technical and economic aspects. Risks are often studied separately according to the consequences of concern:

- Economic risk (rate of interest, inflation, exceeding of budget, changing traffic patterns);
- Operational risk (accidents, loss of lives, impact to environment, disruption of the traffic, loss of assets, loss of income);
- Construction risks (failure to meet time schedule or quality standards, unexpected ground conditions, accidents).

Economic risks in the project may be important for decisions on whether to initiate the project at all. The construction risk may have important implications on the selection of the structural concept and construction methods.

#### Risk Management Framework

The main risk management components are shown in Figure 4.2. The risk policy is formulated by the owner in few words: “The safety of the transportation link must be comparable with the safety for the same length of similar traffic on land.”

The risk acceptance criteria are an engineering formulation of the risk policy in terms of upper limits of risk. The risk policy also specifies the types of risk selected to be considered, typically user

fatalities and financial loss. In some cases, other risks are specifically studied, e.g., risk of traffic disruption and risk of environmental damage, but these risks may conveniently be converted into financial losses.

The risk analysis consists of a systematic hazard identification and an estimation of the two components of the risk, the likelihood and the consequence. Finally, the risk is evaluated against the acceptance criteria. If the risk is found unacceptable, risk-reducing measures are required. It is recommended to develop and maintain an accurate accounting system for the risks and to plan to update the risk assessment in pace with the project development.

In the following, three common risk evaluation methods are discussed: fixed limits, cost efficiency, and ALARP, i.e., as low as reasonably practicable.

*Fixed limits* is the classical form of acceptance criteria. Fixed limits are also known from legislation and it may easily be determined whether a determined risk is acceptable or not. On the other hand, the determination of limits, which can ensure an optimal risk level, may be difficult.

With a pure *cost efficiency* consideration, an upper limit is not defined, but all cost-efficient risk-reducing measures are introduced. For this cost–benefit consideration it is necessary to establish direct quantification of the consequences in units comparable to costs.

The *ALARP* method applies a cost–benefit consideration in which it, however, is stated that the risk shall be reduced until the cost of the reduction measures is in disproportion with the risk-reducing effect. This will result in a lower risk level than the pure cost efficiency. In ALARP a constraint of the acceptable risk is further introduced as an upper limit beyond which the risk is unconditionally unacceptable.

Often it is claimed that society regards one accident with 100 fatalities as worse than 100 accidents each with one fatality. Such an attitude toward risk aversion can be introduced in the risk policy and the risk acceptance criteria. The aversion against large accidents can also be modeled with aversion factors that are multiplied on the consequences of accidents with many fatalities; the more fatalities, the higher the factor. The sensitivity of the evaluations of risk should be considered by the representation of the uncertainty of the information in the models.

### **Risk Studies in Different Project Phases**

The general result of the risk management is a documentation of the risk level, basis for decisions, and basis for risk communication. The specific aims and purposes for risk management depend on the phase of the project. Here some few examples of the purposes of risk management in conceptual study, tender design, detailed design, and operation, are given.

During initial studies, the risk should be crudely analyzed using more qualitative assessments of the risks. A risk management framework should be defined early in the design process. In the beginning of the project, some investigations should be initiated in order to establish a basis for the more-detailed work in later phases; for example, vessel traffic observations should be performed to provide the basis for the estimation of vessel impact probability. In later phases detailed special studies on single probabilities or consequences may be undertaken.

In the conceptual study the most important activities are to identify all relevant events, focus on events with significant risk contributions and risks with potential impact on geometry (safety, rescue, span width). Extreme event loads are established based on the risk studies. In the tender design phase, the main risks are examined in more detail, in particular risks with potential impact on the project basis. In the detailed design phase, the final documentation of the risk level should be established and modifications to the operational procedures should be made.

### **4.3.6 Aesthetic Requirements**

The final structures and components of a fixed link are a result of a careful aesthetic appraisal and design of all the constituent elements. The purpose of aesthetic requirements is to obtain an optimal

technical and sculptural form of individual elements and to obtain an overall aesthetic quality and visual consistency between the elements and the setting. Although difficult, it is recommended to establish guidelines for aesthetic questions.

### **4.3.7 Navigation Conditions**

The shipping routes and the proposed arrangement for a major bridge across navigable waters may be such that both substructure and superstructure could be exposed to vessel collisions. General examples of consequences of vessel collisions are as follows:

- Fatalities and injuries to users of the bridge and to crew and vessel passengers;
- Pollution of the environment, in the case of an accidental release of the hazardous cargo;
- Damage or total loss of bridge;
- Damage or total loss of vessels;
- Economic loss in connection with prolonged traffic disruption of the bridge link.

A bridge design that is able to withstand worst-case vessel impact loads on other piers than the navigation piers is normally not cost-effective. Furthermore, such a deterministic approach does not reduce the risk to the environment and to the vessels. Therefore, a probabilistic approach addressing the main risks in a systematic and comprehensive way is recommended. This approach should include studies of safe navigation conditions, vessel collision risk analysis and vessel collision design criteria, as outlined below.

Navigation risks should be addressed as early as possible in the planning phases. The general approach outlined here is in accordance with the IABSE Green Ship Collision Book [4] and the AASTHO Guide Specification [5]. The approach has been applied in the development of the three major fixed links discussed in Section 4.4.

### **Safe Navigation Conditions**

Good navigation conditions are a prerequisite for the safe passage of the bridge such that vessel collisions with the bridge will not occur under normal conditions, but only as a result of navigation error or technical failure on-board during approach.

The proposed bridge concept should be analyzed in relation to the characteristics of the vessel traffic. The main aspects to be considered are as follows:

- Preliminary design of bridge;
- Definition of navigation routes and navigation patterns;
- Data on weather conditions, currents, and visibility;
- Distribution of vessel movements with respect to type and size;
- Information on rules and practice for navigation, including use of pilots and tugs;
- Records of vessel accidents in the vicinity of the bridge;
- Analysis of local factors influencing the navigation conditions;
- Identification of special hazards from barges, long tows and other special vessels;
- Future navigation channel arrangements;
- Forecast of future vessel traffic and navigation conditions to the relevant study period;
- Identification of largest safe vessel and tow and of preventive measures for ensuring full control with larger passing vessels.

### **Vessel Collision Analysis**

An analysis should be used to support the selection of design criteria for vessel impact. Frequencies of collisions and frequencies of bridge collapse should be estimated for each bridge element exposed to vessel collision. Relevant types of hazards to the bridge should be identified and modeled, hazards

from ordinary vessel traffic which is laterally too far out of the ordinary route, hazards from vessels failing to turn properly at a bend near the bridge, and from vessels sailing on more or less random courses.

The frequencies of collapse depend on the design criteria for vessel impact. The overall design principle is that the design vessels are selected such that the estimated bridge collapse frequency fulfills an acceptance criterion.

### **Vessel Collision Design Criteria**

Design criteria for vessel impact should be developed. This includes selection of design vessels for the various bridge elements which can be hit. It also includes estimates of sizes of impact loads and rules for application of the loads. Both bow collisions and sideways collisions should be considered. Design capacities of the exposed girders against impact from a deck house shall be specified.

The vessel impact loads are preferably expressed as load indentation curves applicable for dynamic analysis of bridge response. Rules for application of the loads should be proposed. It is proposed that impact loads will be estimated on the basis of general formulas described in Ref. [4].

### **4.3.8 Wind Conditions**

Bridges exposed to the actions of wind should be designed to be consistent with the type of bridge structure, the overall wind climate at the site, and the reliability of site-specific wind data. Wind effects on traffic could also be an important issue to be considered.

#### **Susceptibility of Bridge Structures to Wind**

Winds generally introduce time-variant actions on all bridge structures. The susceptibility of a given bridge to the actions of wind depends on a number of structural properties such as overall stiffness, mass, and shape of deck structure and support conditions.

Cable-supported bridges and long-span beam structures are often relatively light and flexible structures in which case wind actions may yield significant contributions to structural loading as well as influence user comfort. Site-specific wind data are desirable for the design. Engineering codes and standards often provide useful information on mean wind properties, whereas codification of turbulence properties are rare. Guidelines for turbulence properties for generic types of terrain (sea, open farmland, moderately built-up areas) may be found in specialized literature. If the bridge is located in complex hilly/mountainous terrain or in the proximity of large structures (buildings, bridges, dams), it is advisable to carry out field investigations of the wind climate at the bridge site. Important wind effects from isolated obstacles located near the planned bridge may often be investigated by means of wind tunnel model testing.

In general, it is recommended that aerodynamic design studies be included in the designs process. Traditionally, aerodynamic design have relied extensively on wind tunnel testing for screening and evaluation of design alternatives. Today, computational fluid dynamics methods are becoming increasingly popular due to speed and efficiency as compared with experimental methods.

#### **Wind Climate Data**

The properties of turbulence in the atmospheric boundary layer change with latitude, season and topography of the site, but must be known with a certain accuracy in order to design a bridge to a desired level of safety. The following wind climatic data should be available for a particular site for design of wind-sensitive bridge structures:

Mean wind:

- Maximum of the 10-min average wind speed corresponding to the design lifetime of the structure;
- Vertical wind speed profile;
- Maximum short-duration wind speed (3-s gust wind speed).



Turbulence properties (along-wind, cross-wind lateral, and cross-wind vertical):

- Intensity;
- Spectral distribution;
- Spatial coherence.

The magnitude of the mean wind governs the steady-state wind load to be carried by the bridge structure and is determinant for the development of aeroelastic instability phenomena. The turbulence properties govern the narrowband random oscillatory buffeting response of the structure, which is similar to the sway of trees and bushes in storm winds.

#### **4.3.9 Earthquake Conditions**

Structures should be able to resist regional seismic loads in a robust manner, avoiding loss of human lives and major damages, except for the very rare but large earthquake. The design methods should be consistent with the level of seismicity and the amount of available reliable information. Available codes and standards typically do not cover important lifeline structures such as a fixed link, but they may be used for inspiration for the development of a design basis.

#### **4.3.10 Ice Conditions**

The geographic location of a bridge site indicates whether or not ice loads are of concern for that structure. The ice loads may be defined as live loads or extreme event loads (exceptional environmental loads which are not included in live loads).

From recent studies carried out for the Great Belt link, the following main experience was obtained:

- Ice loads have a high dynamic component very likely to lock in the resonance frequencies of the bridge structure;
- Bearing capacity of the soil is dependent on number and type of load cycles, so dynamic soil testing is needed;
- Damping in soil and change of stiffness cause important reductions in the dynamic response;
- If possible, the piers should be given an inclined surface at the water level;
- High ductility of the structure should be achieved.

#### **4.3.11 Costing Basis**

The cost estimate is often decisive for the decision on undertaking the construction of the link, for selection of solution models, and for the selection of concepts for tendering. The estimate may also be important for decisions of detailed design items on the bridge.

##### **Cost Uncertainty Estimation**

To define the cost uncertainty it may be helpful to divide it into two conceptions which may overlap: (1) the uncertainties of the basis and input in the estimation (mainly on cost and time) and (2) risk of unwanted events. The uncertainty is in principle defined for each single item in the cost estimate. The risks can in principle be taken from a construction risk analysis.

##### **Cost Estimates at Different Project Phases**

Cost estimates are made in different phases of the planning of a project. In the first considerations of a project, the aim is to investigate whether the cost of the project is of a realistic magnitude and whether it is worthwhile to continue with conceptual studies. Later, the cost estimates are used to compare solution concepts, and to evaluate designs and design modification until the final cost

estimate before the tender is used to evaluate the overall profitability of the project and to compare with the received bids. Different degrees of detailing of the estimates are needed in these stages. In the early phases an “overall unit cost” approach may be the only realistic method for estimating a price, whereas in the later phases it is necessary to have a detailed breakdown of the cost items and the associated risks and uncertainties.

### **Life Cycle Costs**

The life cycle cost is an integration of the entire cost for a bridge from the first planning to the final demolition. The life cycle cost is normally expressed as a present value figure. Hence, the interest rate used is very important as it is a weighting of future expenses against initial expenses.

It shall initially be defined how the lifetime costs are to be considered. For example, disturbance of the traffic resulting in waiting time for the users can be regarded as an operational cost to society whereas it is only a cost for the owner if it influences the users’ behavior so that income will be less.

Important contributors to the life cycle cost for bridges are as follows:

- The total construction cost, including costs for the owner’s organization;
- Future modifications or expansion of the bridge;
- Risks and major repairs;
- Income from the operation of the bridge;
- Demolition costs.

### **Comparison Analysis**

In the development of a project numerous situations are encountered in which comparisons and rankings must be made as bases for decisions. The decisions may be of different nature, conditions may be developing, and the decision maker may change. The comparisons should be based on a planning and management tool which can rationalize, support, and document the decision making.

A framework for the description of the solutions can be established and maintained. This framework may be modified to suit the purpose of the different situations. It is likely that factual information can be reused in a later phase.

The main components of the comparison can be as follows:

- Establishment of decision alternatives;
- Criteria for evaluation of the alternatives;
- Quantitative assessment of impacts of the various alternatives utilizing an evaluation grid;
- Preference patterns for one or more decision makers with associated importance of criteria;
- Assessment of uncertainties.

The decision maker must define the comparison method using a combination of technical, environmental and financial criteria. Quantitative assessment of all criteria is performed. Decision-making theories from economics and mathematical tools are used.

### **Establishment of Alternatives and Their Characteristics**

All decision alternatives should be identified. After a brief evaluation, the most obviously nonconforming alternatives may be excluded from the study. In complex cases a continued process of detailing of analysis and reduction of number of alternatives may be pursued. The selection of parameters for which it is most appropriate to make more-detailed analyses can be made on the basis of a sensitivity analysis of the parameters with respect to the utility value.

Risks may be regarded as uncertain events with adverse consequences. Of particular interest are the different risk pictures of the alternatives. These risk pictures should be quantified by the use of preferences so that they can be part of the comparison.

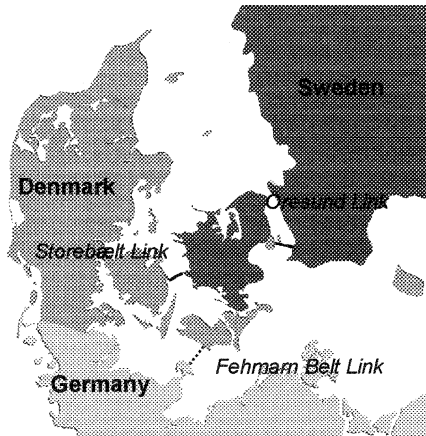


FIGURE 4.3 Denmark and neighboring countries.

### Comparisons at Different Project Stages

After the initial identification of all possible solution models, the purpose of the first comparison may be to reduce the number of solution models to be investigated in the later phases. The solution models may here be alternative design concepts. In this first ranking the detail of the analysis should be adequate to determine the least attractive solutions with an appropriate certainty. This will in most cases imply that a relatively crude model can be used at this stage. A partly qualitative assessment of some of the parameters, based on an experienced professional's judgment, can be used.

At a later phase decisions should be made on which models to select for tender design, and later in the tender evaluation, which tenderer to award the contract. In these comparisons the basis and the input should be more well established, as the comparison here should be able to select the single best solution with sufficient certainty.

Weighting the criteria is necessary. Although a strictly rational weighting and conversion of these criteria directly into terms of financial units may not be possible, it is often sufficient if the weighting and selection process are shown to the tenderers before the tender.

An example of the comparison and selection process can be the following, which is performed in stages. Each stage consists of an evaluation and shortlisting of the tenders eliminating the low ranked tenders. At each stage the tenderers not on the shortlist are informed about the weak points and they are given the opportunity of changing their tender within a short deadline. At the last stage the remaining tenderers are requested to state their final offer improving on the technical quality and financial aspects raised by the owner during negotiations. Then the owner can select the financially most advantageous tender.

## 4.4 Recent Examples of Fixed Links

### 4.4.1 Introduction

Since the 1980s three major fixed links have been designed or planned in Denmark and neighboring countries, [Figure 4.3](#). A combined tunnel and bridge link for railway and highway traffic has been constructed across the 18-km-wide Storebælt, a 16-km tunnel and bridge link for railway and highway traffic between Denmark and Sweden will be inaugurated in year 2000, and the conceptual study has been completed (1998) for a fixed link across the 19-km-wide Fehmarn Belt between Denmark and Germany.

### 4.4.2 The Storebælt Link

Over the years, more or less realistic projects for a fixed link across the Storebælt have been presented. At 18-km-wide, the belt is part of the inland sea area and divides Denmark's population and economy into nearly equal halves.

The belt is divided into two channels, east and west, by the small island, Sprogø, which has been as an obvious stepping-stone, an integral part of all plans for fixed link projects. The international vessel traffic between the Baltic Sea and the North Sea navigates the eastern channel, whereas the western channel is a national waterway. To bridge the eastern channel has therefore always been the main challenge of the project.

The first tender design for a combined railway and highway bridge across the eastern channel was prepared in 1977–78. However, only 1½ month short of issuing tender documents and call for bids, the progress of the project was temporarily stopped by the government. This was in August 1978. Several state-of-the-art investigations such as vessel impact, fatigue, and wind loads were carried out for two selected navigation spans: a 780-m main span cable-stayed bridge and a 1416-m main span suspension bridge, both designed for a heavy duty double-track railway and a six-lane highway.

The construction of the fixed link was again politically agreed upon on June 12, 1986, and the main principles for the link were set out. It should consist of a low-level bridge for combined railway and highway traffic, the West Bridge, across the western channel; whereas the eastern channel should be crossed by a bored or an immersed tunnel for the railway, the East Tunnel, and a high-level bridge for the highway traffic, the East Bridge.

A company, A/S Storebælt, was established January 23, 1987 and registered as a limited company with the Danish State as sole shareholder. The purpose of the company was to plan, design, implement, and operate the fixed link. The project is financed by government-guaranteed commercial loans to be paid back via user tolls. A/S Storebæltsforbindelsen has published a series of reports on the link structures, see Reference [6–8].

#### The East Bridge

##### Project Development

In 1987 conceptual design was carried out for the East Bridge. The main objectives were to develop a global optimization with regard to the following:

- Alignment, profile, and navigation clearance;
- Position of main navigation channel;
- Navigation span solutions, based on robust and proven design and construction technology;
- Constructable and cost-competitive solutions for the approach spans, focusing on repetitive industrialized production methods onshore;
- Master time schedule;
- Master budget.

In 1989–90 pretender studies, tender design, and tender documents were prepared. During the pretender phase, comparative studies of four alternative main bridge concepts were carried out to evaluate thoroughly the technical, financial, and environmental effects of the range of main spans:

Cable-stayed bridge	916 m main span
Cable-stayed bridge	1204 m main span
Suspension bridge	1448 m main span
Suspension bridge	1688 m main span

Navigation risk studies found only the 1688-m main span adequate to cross the existing navigation route without affecting the navigation conditions negatively. This during tender design was reduced to 1624 m, which together with a relocated navigation route, proved to be sufficient and was selected for tender and construction.

The pylons were tendered in both steel and concrete. For the approach span superstructure, 124-m-long concrete spans and 168-m-long steel spans as well as composite steel/concrete concepts were developed. Although an equally competitive economy was found, it was decided to limit the tender designs to concrete and steel spans. The East Bridge was tendered as SDC.

The tender documents were subdivided into four packages to be priced by the contractors: superstructure and substructure inclusive pylons for the suspension bridge (2) and superstructures and substructures for the approach spans. The tender documents were released to prequalified contractors and consortia in June 1990.

In December 1990 the tenders were received. Eight consortia submitted 32 tenders inclusive smaller alternatives and four major alternatives to the basic tender design.

In October 1991, construction contracts were signed with two international consortia; a German, Dutch, and Danish joint venture for the substructures, inclusive of concrete pylons, and an Italian contractor for an alternative superstructure tender where high-strength steel was applied to a more or less unchanged basic cross section, thereby increasing the span length for the approach spans from 168 m to 193 m.

The suspension span is designed with a main cable sag corresponding to  $\frac{1}{8}$  of span length. The steel bridge girder is suspended from 800-mm-diameter main cables in hangers each 24 m.

The girder is continuous over the full cable-supported length of 2.7 km between the two anchor blocks. The traditional expansion joints at the tower positions are thus avoided. Expansion joints are arranged in four positions only, at the anchor blocks and at the abutments of the approach spans.

The concrete pylons rise 254 m above sea level. They are founded on caissons placed directly on crushed stone beds.

The anchor blocks must resist cable forces of 600,000 tonnes. They are founded on caissons placed on wedge-shaped foundation bases suitable for large horizontal loading. An anchor block caisson covers an area of 6100 m<sup>2</sup>.

The caissons for the pylons, the anchor blocks, and the approach spans as well as for the approach span pier shafts have been constructed at a prefabrication site established by the contractor 30 nautical miles from the bridge site. The larger caissons were cast in two dry docks, and the smaller caissons and the pier shafts for the approach spans on a quay area, established for this purpose. A pylon caisson weighed 32,000 tonnes and an anchor block caisson 36,000 tonnes when they were towed from the dry dock by tug boats to their final position in the bridge alignment.

Both the suspension bridge girder and the approach span girders are designed as closed steel boxes and constructed of few basic elements: flat panels with trough stiffeners and transverse bulkhead trusses. The two approach bridges, 2530 and 1538 m, respectively, are continuous from the abutments to the anchor blocks. The suspension bridge girder is 31.0 m wide and 4.0 m deep; the girder for the approach spans is 6.7 m deep. They are fabricated in sections, starting in Italy. In Portugal, on their way by barge to Denmark, a major preassembly yard was established for girder sections to be assembled, before they were finally joined to full-span girders in Denmark. The East Bridge (Figure 4.4), was inaugurated by the Danish Queen on June 14, 1998 and the link was opened to highway traffic.

#### Project Basis

The project basis was throughout its development reviewed by international panels of experts.

#### Structural Requirements

Danish codes, standards, rules, and regulations were applied wherever applicable and supplemented with specific additional criteria and requirements, regarding various extreme event loads.

#### Environmental

The environmental design criteria required that the construction should be executed with no effect on the water flow through the belt. This was achieved by dredging, short ramps, long spans, and hydraulic shaped piers and pylons. The blocking effect to be compensated for was only about 0.5% of the total flow in the belt.



FIGURE 4.4 Storebælt East Bridge.

### Risk

Risk acceptance criteria were established early and a series of risk analyses regarding train accidents, fire and explosion, ice loads, and vessel collision were carried out to ensure adequate and consistent safety level for the entire link. The acceptance criteria required that the probability of disruption of a duration of more than 1 month should not exceed a specified level, and that the risk level for fatalities for crossing should be comparable to the risk for a similar length of traffic on land. The analyses were followed up by risk management through the subsequent phases to ensure that the objectives were met.

### Navigation

With 18,000 vessel passages each year through the eastern channel, important considerations were given for navigation. Comprehensive vessel simulations and collision analysis studies were performed, leading to an improved knowledge about safe navigation conditions and also to a set of probabilistically based criteria for the required impact resistance of the bridge piers and girders. Vessel impact has been the governing load criterion for all the bridge piers. A vessel traffic service (VTS) system was established mainly for prevention of collision accidents to the low West Bridge.

### Wind

The local wind climate at Storebælt was investigated by measurements from a 70-m-high tower on Sprogø. For the East Bridge, aerodynamic investigations were carried out on 16 different highway girder box section configurations in a wind tunnel. The testing determined the critical wind speed for flutter for the selected girder shape to be 74 m/s which was safely above the design critical wind speed of 60 m/s. For the detailed design an aeroelastic full bridge model of 1:200 scale was tested under simulated turbulent wind conditions.

### The West Bridge

The 6.6-km West Bridge (Figure 4.5) was tendered in three alternative types of superstructure; a double-deck composite girder, triple independent concrete girders side by side, and a single steel box girder. All three bridge alternatives shared a common gravity-founded sand-filled caisson substructure, topped by pier shafts of varying layout.



FIGURE 4.5 Storebælt West Bridge.

Tender documents were issued to six prequalified consortia in April 1988, and 13 offers on the tender solutions as well as three major alternatives and nine smaller alternatives were received from five groups. Tender evaluation resulted in selecting an alternative design: two haunched concrete box girders with a typical span length of 110.4 m, reduced to 81.75 m at the abutments and the expansion joints. The total length was subdivided into six continuous girders, requiring seven expansion joints.

It was originally intended to tender the West Bridge as an SDC, but as an alternative design was selected, the contract ended up being similar to a DB contract.

Altogether, 324 elements, comprising 62 caissons, 124 pier shafts, and 138 girders, have been cast in five production lines at a reclaimed area close to the bridge site. All the elements were cast, moved by sliding, stored on piled production lines, and later discharged without use of heavy gantry cranes. The maximum weight of an element was 7400 tonnes. The further transportation and installation was carried out by *Svanen*, a large purpose-built catamaran crane vessel.

By this concept, which was originally presented in the tender design, but further developed in the contractor's design, the entire prefabrication system was optimized in regard to resources, quality, and time. The bridge was handed over on January 26, 1994.

### The East Tunnel

Two immersed tunnel solutions as well as a bored tunnel were considered for the 9 km wide eastern channel. After tender, the bored tunnel was selected for financial and environmental reasons.

The tunnel consists of two 7.7-m-internal-diameter tubes, each 7412 m long and 25 m apart. At the deepest point, the rails are 75 m below sea level.

Four purpose-built tunnel boring machines of the earth-balance pressure type have bored the tunnels, launched from each end of both tubes. The tunnel tubes are connected at about 250 m intervals by 4.5-m-diameter cross passages which provide safe evacuation of passengers and are the location for all electrical equipment. About 250 m of reinforced concrete cut-and-cover tunnels are built at each end of the bored tubes. The tunnel is lined with precast concrete segmental rings, bolted together with synthetic rubber gaskets. Altogether, 62,000 segments have been produced. A number of protective measures has been taken to ensure a 100-year service life design.





**FIGURE 4.6** Storebælt East Tunnel.

On April 7, 1995, the final tunnel lining segment was installed. Thus, the construction of the tunnel tubes was completed, almost 5 years after work commenced. Railway systems were installed and in June 1997 the railway connection (Figure 4.6) was opened to traffic and changes in the traffic pattern between East and West Denmark started.

#### **4.4.3 The Øresund Link**

The 16-km fixed link for combined railway and highway traffic between Denmark and Sweden consists of three major projects: a 3.7-km immersed tunnel, a 7.8-km bridge, and an artificial island which connects the tunnel and the bridge.

The tunnel contains a four-lane highway and two railway tracks. The different traffic routes are separated by walls, and a service tunnel will be placed between the highway's two directions. The tunnel will be about 40 m wide and 8 m high. The 20 reinforced concrete tunnel elements, 175 m long and weighing 50,000 tonnes, are being prefabricated at the Danish side, and towed to the alignment.

The owner organization of the Øresund link is Øresundskonsortiet, established as a consortium agreement between the Danish company A/S Øresundsforbindelsen and the Swedish company Svensk-Danska Broförbindelsen on January 27, 1992. The two parties own 50% each of the consortium. The purpose of the consortium is to own, plan, design, finance, construct and operate the fixed link across Øresund.

The project is financed by commercial loans, guaranteed jointly and severally between the Danish and the Swedish governments. The highway part will be paid by user tolls, whereas the railway companies of the two countries will pay fixed installments per year. The revenue also has to cover the construction work expenses for the Danish and Swedish land-based connections.

Prequalified consultants were asked in February 1993 to prepare a conceptual design, as part of a proposal to become the in-house consultant for the owner. Two consultants were selected to prepare tender documents for the tunnel, the artificial island and the bridge, respectively.

#### **The Øresund Bridge**

In July 1994, the Øresundskonsortiet prequalified a number of contractors to build the bridge on a design and construct basis.





**FIGURE 4.7** Øresund Main Bridge.

The bridge was tendered in three parts; the approach bridge from Sweden, the high-level bridge with a 490-m main span and a vertical clearance of 57 m, and the approach spans toward Denmark. Two solutions for the bridge were suggested: primarily, a two-level concept with the carriageway on the top deck and the two-track railway on the lower deck; secondarily a one-level bridge. Both concepts were based on cable-stayed main bridges.

Five consortia were prequalified to participate in the competition for the high-level bridge, and six consortia for the approach bridges. In June 1995, the bids for the Øresund Bridge were delivered. The two-level concept was selected as the financially most favorable solution. In November 1995, the contract for the entire bridge was awarded to a Swedish–German–Danish consortium.

The 7.8-km bridge includes a 1090-m cable-stayed bridge (Figure 4.7) with a main span of 490 m. The 3013 and 3739 m approach bridges have spans of 140 m. The entire superstructure is a composite structure with steel truss girders between the four-lane highway on the upper concrete deck and the dual-track railway on the lower deck.

Fabrication of the steel trusses and casting of the concrete deck of the approach bridges are carried out in Spain. The complete 140-m-long girder sections, weighing up to 7000 tonnes, are tugged on flat barges to the bridge site and lifted into position on the piers. Steel trusses for the cable-stayed bridge are fabricated in Sweden and transported to the casting yard close to the bridge site, where the concrete decks are cast.

On the cable-stayed bridge the girder will also be erected in 140-m sections on temporary supports before being suspended by the stays. This method is unusual for a cable-stayed bridge, but it is attractive because of the availability of the heavy-lift vessel *Svanen*, and it reduces the construction time and limits vessel traffic disturbance. (*Svanen* was, as mentioned earlier, purpose-built for the Storebælt West Bridge. After its service there *Svanen* crossed the Atlantic to be upgraded and used for the erection works at the Confederation Bridge in Canada. Back again in Europe *Svanen* performs an important job at Øresund). During the construction period two VTS systems have been in operation, the Drogden VTS on the Danish side, and the Flint VTS on the Swedish side. The main tasks for the VTS systems are to provide vessels with necessary information in order to ensure safe

navigation and avoid dangerous situations in the vicinity of the working areas. The VTS systems have proved their usefulness on several occasions.

The cable system consists of two vertical cable planes with parallel stays, the so-called harp-shaped cable system. In combination with the flexural rigid truss girder and an efficient pier support in the side spans, a high stiffness is achieved.

The module of the truss remains 20 m both in the approach and in the main spans. This results in stay cable forces of up to 16,000 tonnes which is beyond the range of most suppliers of prefabricated cables. Four prefabricated strands in a square configuration have therefore been adopted for each stay cable.

The concrete pylons are 203.5 m high and founded on limestone. Caissons, prefabricated on the Swedish side of Øresund, are placed in 15 m water depth, and the cast-in-place pylon shafts are progressing. Artificial islands will be established around the pylons and nearby piers to protect against vessel impact. All caissons, piers, and pier shafts are being prefabricated onshore to be assembled offshore. The bridge is scheduled to be opened for traffic in year 2000.

## **Project Basis**

### **General Requirements**

The Eurocode system was selected to constitute the normative basis for the project. Project application documents (PADs) have been prepared as companion documents to each of the Eurocodes. The PADs perform the same function as the national application documents (NADs) developed by the member countries implementing the Eurocodes.

The partial safety and load combination factors are determined by reliability calibration. The target reliability index of  $\beta = 4.7$ , specified by the owner, corresponds to high safety class as commonly used for important structures in the Nordic countries.

In addition to the Eurocodes and the PADs, general design requirements were specified by the owner to cover special features of a large civil work. This is in line with what is normally done on similar projects. The general design requirements cover the following areas:

- Functional and aesthetic requirements as alignment, gradients, cross sections, and clearance profiles;
- Civil and structural loads, load combinations, and partial safety coefficients; methods of structural analysis and design;
- Soil mechanics requirements to foundation design and construction, including soil strength and deformation parameters;
- Mechanical and electrical requirements to tunnel and bridge installations, including systems for supervision, control and data acquisition (SCADA), power distribution, traffic control, communication.

### **Risk**

LHRisk acceptance criteria were developed such that the individual user risk for crossing the link would be equal to the average risk on a highway and railway on land of similar length and traffic intensity. In addition, the societal risk aspects concerning accidents with larger numbers of fatalities were controlled as well.

The ALARP-principle — as presented in Section 4.3 — was applied to reduce consequences from risks within a cost–benefit approach. Especially the disruption risks were controlled in this way. Risk-reducing measures were studied to reduce the frequency and consequences of hazardous events. The analyses carried out addressed main events due to fire, explosion, toxic releases, vessel collision and grounding, flooding, aircraft crash, and train derailment.

### **Navigation**

Øresund is being used by local vessel traffic and vessels in transit up to a certain limit set by the water depth in the channels Drogden and Flinterännan. The Drogden channel near the Danish coast

will be crossed by the immersed tunnel and only requirements regarding accidental vessel impact to tunnel structures have been specified. The Flinterännan near the Swedish coast is being crossed by the bridge, and the navigation route will be improved for safety reasons. Design criteria against vessel impact have been specifically developed on a probabilistic basis, and main piers will be protected by artificial islands.

#### **4.4.4 The Fehmarn Belt Crossing**

In 1995, the Danish and German Ministry of Transport invited eight consulting consortia to tender for the preliminary investigations for a fixed link across the 19-km-wide Fehmarn Belt.

Two Danish/German consortia were selected; one to carry out the geological and the subsoil investigations, and the other to investigate technical solution models, the environmental impact, and to carry out the day-to-day coordination of all the investigations.

In the first phase, seven different technical solutions were investigated, and in the second phase five recommended solutions were the basis for a concept study:

- A bored railway tunnel with shuttle services;
- An immersed railway tunnel with shuttle services;
- A combined highway and railway bridge;
- A combined highway and railway bored tunnel;
- A combined highway and railway immersed tunnel.

With a set of more detailed and refined functional requirements, various concepts for each of the five solution models have been studied in more detail than in the first phase. This concept study was finalized in early July 1997 with the submission of an interim report. The conceptual design started in December 1997 and is planned to last 7 months. To provide an adequate basis for a vessel collision study and the associated part of the risk analysis, vessel traffic observations are carried out by the German Navy. In parallel, the environmental investigations are continued, whereas the geological and the subsoil investigations are concluded.

The results of the study will constitute the basis for public discussions and political decisions whether or not to establish a fixed link, and also which solution model should be preferred.

## **References**

1. The Danish Transport Council, Facts about Fehmarn Belt, Report 95-02, February 1995.
2. The Danish Transport Council, Fehmarn Belt. Issues of Accountability, Report 95-03, May 1995.
3. The Interaction between Major Engineering Structures and the Marine Environment, Report from IABSE Colloquium, Nyborg, Denmark, 1991.
4. Ole Damgaard Larsen: Ship Collision with Bridges, IABSE Structural Engineering Documents, 1993.
5. Guide Specification and Commentary for Vessel Collision Design of Highway Bridges, Vol. 1, Final Report, AASHTO, 1991.
6. The Storebælt Publications: East Tunnel, A/S Storebæltsforbindelsen, København, Denmark, 1997.
7. The Storebælt Publications: West Bridge, A/S Storebæltsforbindelsen, København, Denmark, 1998.
8. The Storebælt Publications: East Bridge, A/S Storebæltsforbindelsen, København, Denmark, 1998.