SUMMARY

Jacques Combault, born in 1943, has been working as bridge designer for more than 30 years, with Campenon Bernard and GTM, both being now companies of VINCI (France). Recently involved in major projects abroad, he is currently Consultant and Technical advisor.

The conceptual design of a bridge including foundations, supports and deck, has to be carried out according to the required clearances, the selected materials and the possible construction methods. This usually leads to applicable bridge types which are feasible and which can be compared in terms of cost, aesthetics and durability.

The bases of the selection process, taking into account all the key parameters governing the conceptual design of bridges, are detailed in the following pages. Several ways of classifying bridges are proposed and finally discussed, for short and medium span bridges which have to be made preferably continuous.

The necessary interaction between design and construction methods is emphasised as it lead to the development of new structural concepts, in terms of materials (external prestressing), combination of materials (corrugated steel webs, web trusses), prefabrication and assembly, during the last 30 years.

KEYWORDS

Bridges, Classification, Concepts, Continuity, Design, Steel and Concrete, Reinforced and Prestressed Concrete, Composite Structures.
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1. Introduction

The concept of a bridge has to be selected according to a certain number of specific parameters which are related to the characteristics of the new link to be built and usually specified by the representatives of the owner (State, Concessionaire or any relevant Private Organisation); these characteristics are typically:

- the location of the bridge
- the purpose of the bridge (Motorway, Highway, Railway)
- the importance of the bridge and the corresponding durability concerns
- the completion date

Consequently, the Designer, as well as the Contractor at a later stage, has to take into account the corresponding constraints prior to selecting the bridge type and construction methods:

The location of the bridge clearly leads to major inputs such as:

- geographical and geotechnical conditions
- crossing characteristics (valley, roads, railways, river) and corresponding span distribution
- possible natural and human made hazards (wind, earthquakes, impacts)

The purpose of the bridge generally leads to:

- applicable specifications
- relevant structural dimensions and details

The importance of the bridge and required durability finally lead to specify:

- the materials to be used
- the way these materials have to be prepared and implemented

2. Classification of Bridges

Classification of bridges may be achieved in many ways:

- according to how they look like longitudinally, or transversally
- according to the materials to be used or the way they are going to be built

2.1. Longitudinal anatomy of bridges

There are basically two types of structural elements [1]:

- those transferring forces acting upon them by axial forces
- those elements resisting forces acting on them by bending
When judiciously combined (Figure 1), these two structural elements lead to five types of bridges:

- inclined leg bridges and arches, when axial force is compression
- girder bridges
- cable stayed and suspension bridges, where axial force is tension

![Structural components](image)

**Figure 1**: Structural components are basically resisting axial forces and bending.
Judiciously combined, they give rise to five types of Bridges

It is worth mentioning that most of them have been invented by nature and progressively investigated, understood and improved by Engineers. It has also to be noticed that girders are indeed resisting thanks to the simultaneous action of tension and compression elements, either visible (trusses) or non visible (beams) and might therefore be considered as a combination of both.

### 2.2. Materials

During the last two hundred years, a number of new materials have been created. Steel and concrete replaced wood and stone while structures and forms were simultaneously adapted to the evolution of resistant materials:

- Concrete is heavy and non resisting to tensile forces but it is definitely recognised as being well adapted to compression members [5]
- Steel is resisting high compressive and tensile stresses and therefore relatively light. Meanwhile, as slender elements are subject to buckling, it is preferably used to form tension members or cables

Performances of both steel and concrete have been considerably improved during the last twenty years in such a way that structures which would have not been possible in the past have become feasible.
2.3. **Transversal anatomy of bridges**

Depending on the materials or combination of materials being used, typical cross sections of bridges (Figure 2) are classified as slabs (concrete), beams and box girders (open or not) [2].

![Diagram of typical cross-sections of bridge decks](https://via.placeholder.com/150)

**Concrete**
- Slab

**Composite**
- Embedded Steel Beams
- T Girders
- Open Box Girders

**Steel**
- I Beam
- Box Girders

*Figure 2: Typical Cross-Sections of Bridge Decks*

Most of the components of these transversal structures essentially resist to loads by bending.

For a given crossing, applicable cross sections are selected according to span length, structural type, deck width, available materials and construction methods. Box girders are generally preferred for curved bridges or long spans requiring aerodynamic shaping and torsional stiffness (Figure 3).

While concrete structures appears to be heavy and steel structures to be light, it must be recognised that fabrication of steel structures is much more sophisticated as many stiffeners have to be provided to eliminate any buckling or plate out-of-plane risk.

This is the reason why, when possible, the association of steel and concrete in a composite cross-section highly simplifies the steel design and fabrication.
2.4. Construction Methods

Due to the necessary connection between cast-in-situ foundations and pier shafts, bridge supports are generally cast in place.

Concrete deck structures are either cast in place (i.e. at their final location), or built in a practical place prior to being moved to their final location, or prefabricated in many pieces then transported and assembled at their final location. This leads to classify the construction methods as follows (Table 1):

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<th>CAST-IN-SITU METHODS</th>
<th>DISPLACEMENT METHODS</th>
<th>PREFABRICATION</th>
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<tr>
<td>Forms on Scaffolding</td>
<td>Translation</td>
<td>Beams placed with cranes or launching gantries</td>
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<td>Forms on Temporary Supports</td>
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Table 1: Classification of Concrete Structures according to Construction Methods
Steel deck components are generally prepared in a factory before being delivered and assembled on the construction site. Incremental launching as well as balanced cantilever assembly are the most common placing methods in use for the construction of steel decks. Concrete slab of steel concrete composite bridge decks are either easily cast in place or made of prefabricated slab panels.

3. Governing Parameters at the Conceptual Design Stage

In relation with the site characteristics, the materials to be used, the selected longitudinal and transversal concept of the bridge and the applicable construction methods, which have to be selected as a whole at the conceptual design stage, the deck structure is more and more commonly made continuous.

Continuity is applicable to all kind of bridges and a lot of examples can be found in the past and recent years to emphasise this powerful concept.

Short and medium spans made of classical constant depth girders, all being either made of concrete, steel or combination of both, show many spectacular structures which are good examples of continuous bridge decks and the success of these bridges has to be associated with several main advantages.

As it can be seen, from some examples, continuous structures are generally nice and continuity leads undoubtedly to a certain standard in terms of aesthetics and comfort for users.

But continuity means also many theoretical and practical advantages which can be appreciated through simple calculations or developments of a wide range of construction methods. In addition to that the combination of modern construction methods and of a continuous external prestressing can lead to a fine tuning of the permanent forces to resist the traffic loading.

3.1. From Discontinuity to Continuity

It is not in fact possible to separate clearly all the key parameters governing the choice which could be made, with regard to continuity or discontinuity, as they are many and interfering all together; but some characteristics might be considered as generally representative of one technology with regard to the other one.

3.2. Discontinuous Bridges

Discontinuity appears to be, first, the simplest concept. Basically, discontinuity comes from the quite simple and natural idea of placing beams simply supported at both ends one against each other to span small consecutive gaps on a given width. No other system seems to be that simple, both from a design and construction point of view, whatever the material used to make the beams is.

3.2.1. Major Characteristics of Bridges with discontinuities

Although it could be possible to connect longitudinally successive beams of any shape, I shape for beams made of steel or concrete to support a slab, seems to be a major characteristic of bridge deck with no continuity.
The way the beams are supported is another major characteristic. Simple supports at both ends is very common although bridges consisting of cantilevering boxes built-in the piers, either made of steel or concrete, have been built intensively in several countries for many years in order to accommodate span length or to use the very efficient balanced cantilever erection method to build bridges.

These various corresponding static schemes can be considered as the different stages which have been necessary in bridge engineering to move from the simple initial concept to the more sophisticated concept of continuous structures.

3.2.2. Advantages

It is a fact that statically determined structures are basically discontinuous but the calculations to be carried out are easy and therefore attractive.

Simple beams are not sensitive to imposed displacements, mainly to differential settlements or temperature gradients, and were probably preferred to any other solution when engineers did not master foundation design.

In addition to that, placing parallel girders can be easily managed by adjusting the number of girders to cover the required width and therefore the weight of the girders. As long as the lifting and placing equipment was not as powerful as it can be today, this was a serious advantage which allowed solving all problems of interaction between design and construction.

3.2.3. Disadvantages

A lot of disadvantages could be identified by a rigorous comparison with continuous bridges.

Nevertheless, it can be stated first that simply supported bridges do not allow long spans.

Secondly when the beams are long a heavy launching device is needed.

Due to the number of beams, piers have to be wide or to consist of a shaft topped by a big cross beam (Figure 4).

In terms of deflection, these beams, if made of concrete, are very sensible to creep and the only way to avoid that is to implement a partial prestressing equilibrating the dead weight only.
Although discontinuity can be overcome by a partial continuity of the beams at the level of the top slab the use of beams leads to a large number of joints which are a weak point of these structures in terms of comfort.

Finally, aesthetics of such structures is generally considered to be poor even if it can be improved by designing the piers in an elegant way.

3.3. Continuous Bridges

Continuity does not mean necessarily monolithism and does not apply to all types of cross sections.

If typical concrete I or U beams are used, it seems unnecessary and not logical to make them continuous as long as it requires sophisticated or heavy connection concepts (big cross beam resting on bearings). Then, box girders will be the only type of concrete deck considered hereafter.

Under certain circumstances (piers high enough, flexible supports) the concrete structures can be made monolithic, combining then several advantages which will be identified later.

Of course, these remarks do not apply to steel or composite bridge decks which can be economically designed using I beams (of constant or variable depth) and which cannot be made connected rigidly to the piers.

3.3.1. Theoretical Advantages

It is not useless to mention once more the considerable advantages such bridges demonstrate in terms of aesthetic and comfort as long as the problem of creep in continuous concrete structures is well appreciated.

Generally speaking, continuity allows for a good distribution of stresses in the bridge decks whatever the construction scheme is.

Figure 5 : Comparison of the Bending Moments generated in discontinuous and continuous spans
The diagram of permanent bending moments generated in a multi-span deck shows how these bending moments are well distributed all along the span length if the combination of construction methods and prestressing has been chosen to get a fine tuning of the permanent forces to resist the traffic loading (Figure 5).

At Serviceability Limit States, the effects of traffic loads are also less severe than for a simply supported span even if the most unfavourable bending moments at piers are generated by the loading of two consecutive spans and if negative moments can be generated at mid-span.

Nevertheless, on the contrary of what happens in simply supported spans, which are governed by the only behaviour of the cross section located at mid-span under a single traffic loading, the behaviour of continuous bridge deck depends on a lot of parameters as long as the most unfavourable load cases are absolutely different for each governing cross sections.

This fundamental property has several important consequences. The major one concerns the Ultimate Limit States as it is clear that 3 plastic hinges have to develop for the failure of a typical span of a continuous deck when one hinge only is critical for a simply supported deck. The most unfavourable effects being produced by quite different loading combination, it is a fact that the safety factor which can be reached at ultimate limit states on such a continuous bridge is much higher than for a simply supported span.

This list of advantages would not be complete if pier-deck continuity was not mentioned.

The fact is that, in deep valleys, when pier shaft are high and flexible, the deck can be built in the piers making then the piers participating efficiently to the general behaviour of the structure and therefore to the strength of the deck.

3.3.2. Practical Advantages

Practical advantages of continuity are either direct consequences of theoretical ones (as for examples aesthetics (Figure 6), comfort, and economy) or the result of the wide variety of construction methods which can be imagined in conjunction with the use of a modern prestressing tendon layout.

Figure 6: Continuous bridges are beautiful and comfortable – La Gruyere Bridge (Switzerland)
3.3.3. Disadvantages

The main disadvantage is theoretical. Strain constraint, which is a pure result of continuity, unavoidably leads to significant bending moments under temperature gradients, these bending moments being unfavourable at mid-span, as they are cumulating with the effects of other loads. This is the reason why continuity of simple beams is not easy to do, as temperature gradients are generating tremendous positive bending moments when positive permanent bending moments are greatly reduced to a minimum which does not allow for an efficient tendon layout.

In addition, such structures are clearly sensitive to differential settlements and creep of concrete which have then to be taken into account with a high factor of safety.

4. Short and Medium Span Bridges

According to the above, classical short and medium span bridges are therefore made preferably continuous, using either concrete or steel concrete composite structures. As a result, the cross section of such bridges has to be designed for resisting negative bending moments at support locations and the deck generally consists of an open box girder when spans are short enough or of a box girder for longer spans.

4.1. Prestressed concrete bridges

Any construction method mentioned in Table 1 is applicable to prestressed short and medium span concrete bridge decks.

4.1.1. Construction and Design of Cast-in-Place Bridge Decks

When the bridge is located in a convenient site with a flat area which is not congested by roads or railways, when it does not have to cross water and when the soil has a good bearing capacity, the simplest way to build the bridge is to cast it span by span, in forms supported by scaffoldings or temporary supports, according to the sketch of Figure 7.

Figure 7 : An easy way to build short span bridges in a convenient site
**Construction in Self-Supported Forms**

But as soon as the bridge must span a congested area, or a stretch of water, the best way to build a multi span bridge with short spans is to use self-launching equipment consisting of a steel structure supporting the forms as shown in Figure 8.

![Figure 8: Construction of short span concrete bridges using self launching equipment](image)

As the launching equipment and the associated forms are generally complicated and heavy, it makes sense to use this erection process for small spans (30 to 40 meters long) in conjunction with an open box design of the deck.

![Figure 9: Self-launching equipment used for the construction of La Gruyere Bridge](image)

Depending on the required width of the crossing, the span-to-depth ratio of the deck will be then in the range 18 – 20 and applicable cross sections of such continuous open boxes will be as shown in Figure 10.

![Figure 10: Typical Cross Sections of Decks cast in place in a Launching Equipment](image)
Spans are generally cast in sections located in between the so-called “zero-moment points”. Under these conditions and taking into account creep effects, the final distribution of the permanent bending moments in the bridge is not far from what it would be if the bridge was cast in one sequence only on a full length scaffolding, the PT tendon layout being adapted to all construction sequences and therefore as shown in Figure 11.

![Figure 11: Typical PT tendon layout for a span-by-span cast-in-Situ Bridge Deck](image)

Of course, the construction of the deck using a self-launching formwork is also applicable to 40 to 60 meter long spans in conjunction with a box design, but it has to be emphasised that other and more efficient construction methods (Cf. § 4.1.2) are preferred for practical reasons.

**Balanced Cantilever Construction**

Indeed, when spans of the bridge are longer than 60 meters, cast-in-situ decks have to be built according to the basic principles of the balanced cantilever method which is commonly used for erecting short and medium span bridges all around the world while other construction methods are not applicable.

![Figure 12: Construction stages of the Balanced Cantilever method](image)
Using form travellers, the bridge deck construction progresses symmetrically from the piers (Figure 12) in short sections (segments), typically 3.00 to 4.50 m long, up to the middle of each span, the successive balanced cantilevers built that way being finally made continuous.

Form travellers (Figure 13) are installed on starting deck sections (pier segment) which have to be temporarily fixed to the piers to resist the unbalanced loads during construction.

The high efficiency and success of the method is not only due to the fact that it is possible to build long enough spans made of a variable depth box girder; it is also due to the fact that:

- distributed loads generated by the dead weight of variable depth cantilever are the most significant where they are the less unfavourable;
- negative bending moments, which are drained towards the pier axis, are fully resisted by the highest and strongest sections of the deck (Figure 14);
- extreme positive bending moments generated by the dead weight (creep effects) are consequently greatly reduced, as well as bending moments generated by live loads in tallest sections at mid span which are less than what they would be in constant depth girders (stiffening effect of the deck near piers);
- available PT units make it possible to finely tune the prestressing force distribution to the bending moment distribution.
Variable depth girders therefore are well adapted to the design of continuous bridges; in addition, when associated to gracefully shaped piers, they generally lead to extremely elegant medium span bridges.

For such variable depth girders, the PT tendon layout consists of three families of tendons:

- the balanced cantilever tendons;
- the closure tendons;
- the continuity tendons;

Another way to build concrete short and medium span bridge decks is to use an incremental launching method, which is recognised to be an easiest and simplest way to perform the necessary construction tasks in the best economical and working conditions as:

- The site installations (offices, cranes, materials, batching plant, forms) are concentrated at the most convenient location and does not normally need to be moved during the whole construction process of the deck;
- Specific equipment to be used is simple;
- Major works are carried out at ground level behind the abutments;
- Casting operations and launching phases are organised to fit with the required construction time.
The method is flexible enough to offer several possibilities according to span lengths of the bridge (Figure 17).

The necessary equipment (Figure 18) mainly consists of:

- A casting bed including the necessary forms;
- A steel launching nose (or a temporary stay cable system);
- The necessary sets of temporary sliding bearings to be installed at each pier for launching sequences (Figure 19);
- A translation device.

The span-to-depth ratio of incrementally launched bridge decks is usually in the range 16 – 18. As any section of typical spans has to resist negative bending moments and high shear stresses when reaching a pier and positive bending when going through mid span, the PT tendon layout is mainly made of straight cables and the deck preferably consist of a constant depth box (Figure 20) with thick webs, though additional deviated PT tendons are generally added after completion of the deck for counteracting dead loads as much as possible.

4.1.3. Prefabricated Concrete Decks

Prefabrication of concrete decks will be mentioned here for short span bridges made of simply supported beams, as the number of bridges designed and built that way has been considerable.
Prefabrication of concrete bridge decks made of box girders opened up so many new horizons to Engineers that it will be extensively developed in a separate part of this document specifically addressing this important topic.

Indeed, the idea of prefabricating concrete beams to build concrete structures has been developed since the very beginning as a consequence of the new possibilities offered by prestressing technology. Though discontinuous bridges were previously criticised, it must be recognised that this construction method has many advantages from a practical point of view:

- Beams are all the same design and simply fabricated on site or in a factory in good conditions
- They are easily transportable and quickly erected using either cranes or self-launching equipment
- Any deck width may be accommodated with an adequate number of beams

Typical applicable cross-sections of bridge deck made of precast beams and PT tendon layout of a prestressed concrete unit are shown in Figure 21.

4.2. **Steel-Concrete Composite Bridges**

Short and medium span bridges are made more and more economical and easy to build by the association of steel and concrete and the combination of their major characteristics.
4.2.1. Construction and Design of classical Composite Bridges

There are different ways of associating steel and concrete in the design of bridges, the most commonly used resulting of the connection of a concrete slab to a steel structure and leading to typical cross sections as shown in Figure 2.

Actually, such an association has the following advantages:

- Composite deck structures are lighter than concrete deck structures and foundation cost is consequently reduced
- Unless subject to abnormal loads, steel structures are generally made simple and consisting of twin I-girders braced at a regular spacing
- Steel structures are easily and quickly erected by using incremental launching
- Either cast in place or made of precast panels, reinforced concrete slab is easily built when steel structure has been launched

In addition, the assembly yard and the launching equipment of the steel structure, as well as the forms of the concrete slab, are very simple (Figure 22).

![Steel structure, launching bearings and cast-in-situ concrete forms](image)

Figure 22 : Steel structure, launching bearings and cast-in-situ concrete forms

This family of composite bridges is well adapted to spans 50 to 80 meters long with a 25 to 30 span length-to-depth ratio.

4.2.2. Construction and Design of Steel Concrete Hybrid Bridges

Though the concept of hybrid construction is essentially beneficial in the field of long span bridges which will be developed in the third part of this document, it also applies to the design of medium span bridges under certain conditions. In fact, the basic principle of the concept is to use the right material at the right place; i.e. concrete where weight is required and not too expensive, steel where weight is detrimental and placing of large components is easy.
As an example of such a powerful concept, Figure 23 shows the most important erection stages of the main span of a bridge over a large river for which delivery, hoisting and final placing of an orthotropic steel box was easy, while construction of the concrete deck of traditional short span approaches was cost effective.

4.3. Steel Bridges

Despite progress made in the fabrication and protection techniques of orthotropic steel boxes, decks of short and medium span bridges are generally not made of steel.

Nevertheless and as previously mentioned, any construction method is applicable to the deck erection of such bridges, should steel would be required for any reason, and some of these construction methods (incremental launching, cantilever erection) are extensively used for the erection of long span bridge decks preferably made of steel.

5. External Prestressing

The idea of external prestressing is not new. Indeed, several bridges were built in France with tendons outside the concrete as early as 1950 but, due to the lack of an available technology at that time, these tendons were in a really bad shape 30 years later.

External tendons were then only used when they were temporary (cantilever stability, blocking pin joints, incremental launching ...) or when there was no other solution (Repair and upgrading of existing structures) and more than 20 years had gone by before this simple idea was brought back into use.

Experience gained with the repair of existing structures, competition between concrete structures and steel-concrete composite structures, development of new structural concepts as well as new construction methods, lead Structural Engineers to revisit and develop the attractive idea of external prestressing which opened up new horizons [3].
5.1. **Practical advantages of external prestressing**

Henceforth, the elimination of tendons which were habitually located inside the concrete (at gussets or spread out in the webs) constitutes a large improvement in the quality of the structure.

### 5.1.1. Better concreting conditions

Ducts placed in the concrete at gussets or in the webs (Figure 24), i.e. at strategic points in the structure, often create a barrier across which the concrete must be poured (especially when ducts overlap one another because of deviations). Eliminating this obstacle makes good concreting much easier.

### 5.1.2. Elimination of threading and tensioning problems

The risks previously mentioned and particular construction methods sometimes lead to problems concerning:

- Cable threading which may be hindered by excessive friction coefficients or obstructions in the ducts themselves
- Tensioning operations due to repeated strand breakages at abrupt changes of slope near anchorages.

In both cases, these mishaps are usually provoked by the fall of fresh concrete on to the tendon groups, by vibrator impact on the ducts and bad jointing between ducts and anchorages. Often respect of good practice at the design stage and particular care during construction will reduce these problems whereas external prestressing will eliminate them entirely.

![Figure 24: Illustration of concreting conditions](image)

![Figure 25: Angles at duct connections and anchorages leading to excessive friction or wire failure](image)
5.1.3. Suppression of discontinuities in tendon profile

Prestressing inside the concrete also means a certain multiplication of the number of anchorages spread throughout the length of the structure. This inevitably leads to abrupt discontinuities in prestressing, to awkward formwork details (for example, short and projecting anchorage blisters) and as a rule generally bad overall conception. The concreting phases must be adapted to the tendon layout and tensioning operations are often numerous.

In this respect external prestressing is much more practical for the designer (Figure 26).

![Figure 26: Continuous PT tendon profile](image)

**Figure 26 : Continuous PT tendon profile**
*(Only connected to the structure at pier and deviation diaphragms)*

5.1.4. Suppression of injection vents in the top slab

When properly conceived, external prestressing only comprises tendons whose high point is near the anchorages in the counter-curve.

This particularity, plus the need for continuous water tight ducts, eliminates the possibility of intercommunication and simplifies grouting procedure and eliminates injection tubes embedded in the concrete emerging on to the road surface.

5.1.5. Possibility of a visual and mechanical checking of PT tendons

It is a great improvement with respect to conventional prestressing to be able to visually check the most part of all the tendons as well as duct joints, grouting operations, the quality of grouting and finally, under certain conditions (according to the method used), the tensile stress in the tendons during the life of the structure.

5.1.6. Possibility of cable replacement or addition

Furthermore, although not absolutely essential, external prestressing can be designed to be replaceable and even reinforced if necessary as long as this possibility is considered in advance.
5.1.7. Possibility of making structure and PT tendons independent

Finally, when tendons are arranged outside the concrete, the extraordinary independence between structures and prestressing opens up new horizons, which engineers are beginning to master (Figure 27). For although the simultaneity of the important steps accomplished during the last five years prevent a dear differentiation of the different causes of the progress made, one thing is certain: the idea of external prestressing was the catalyser for a boom in the geometry and materials (or combinations of materials) which could be associated with prestressing [4].

![Figure 27: Illustration of the independence of the PT tendons with regards to the deck structure](image)

5.2. Theoretical advantages of external prestressing

External prestressing improves, therefore, the general quality of prestressed structures; these advantages are well attuned to the present day trends towards safety, elimination of defects and the option of easy and permanent checking.

Nevertheless safety and durability are also the result of the perfect operation of the structures designed and the contribution to this made by the modern technology of external prestressing is considerable.

5.2.1. Elimination of ducts embedded in concrete

Generally speaking, the elimination of ducts in the concrete reduces the risk of local weakening of the cross-section at locations where concreting is critical and where forces such as transverse bending moments, general and local shear inevitably accumulate.

The suppression of "holes" corresponding to the duct passage along a section throughout the web height puts aside any controversy about web resistance to shear forces. In the absence of such voids during construction and of the heterogeneous state (tendon + grout + duct) in
service it is certain that the compression paths are not deviated and consequently do not become fragile.

In other words, in all important cross-sectional zones (gussets, webs, slabs) external prestressing improves the structural resistance to all the forces applied to it and it does with less materials.

5.2.2. Simplicity of tendon profile

External prestressing tendons present the advantage of being less deviated. The tendon profile is simple and easy to respect. It has many straight sections for which friction coefficients are inexistent because duct wobble is impossible. Recent technological developments eliminate the risk of alignment errors in deviation saddles and anchorage blisters. The curvature friction coefficient, which depends closely upon the technology employed, can be much lower than that normally used for the calculation of friction losses and the final prestressing forces in external prestressing tendons are much higher than those obtained in classical internal prestressing tendons.

5.2.3. Possibility of placing PT tendon anchorages at the best location

Here again, the profile simplicity, which is the result of geometrical and physical analysis, leads to a concentration of anchorages in the diaphragms normally provided at piers and abutments. These diaphragms are naturally massive and clearly adapted to receive the large forces applied by the anchorages.

This disposition is one of the most important advantages of external prestressing (in spite of its apparent discretion) because it eliminates the anchorages spread out along the total length of the structure which are at the origin of high local tensile and shear stresses in areas where the general forces are not sufficient to provide the required resistance (continuity cables in the bottom slab for example).

5.2.4. Structural lightness

The logical consequence of the advantages cited above and therefore of the use of external prestressing is the dead weight saving. For equal structural resistance it is possible to reduce the web thickness, gusset volumes and, as will be seen later, the bottom slab thickness without weakening the cross-section.

On the contrary, the homogeneous character of all the cross-sections throughout the structure is an additional advantage. The load reduction due to lower dead weight is favourable both during service and construction.

5.2.5. Prestressing force efficiency

The improved quality of the prestressing and the reduced cross-sectional area lead to an increase in the stresses resulting from the axial prestressing force.

These factors compensate for the loss of eccentricity which can be encountered with external prestressing and permit a better exploitation of certain construction methods at the time of conception.
5.2.6. Cost of external prestressing

Finally, for the same quality, external prestressing is in principal less expensive than classical prestressing.

Its main advantage is in eliminating repeated installation, adjustment and fixing operations.

However, these cost differences are difficult to appreciate and frequently hidden by the technological improvements in the field of external prestressing which are being progressively developed by engineers during the conception of future projects.

As a matter of fact, the economy of external prestressing is not unanimously recognised: but when it seems to be more expensive than traditional prestressing it must be remembered that it is dismountable and therefore interchangeable, it is continuous and hides no tricks concerning the distribution of forces in the structure.

5.3. Important Applications of external prestressing

It was towards the latter part of the 1970's that the first spectacular applications of external prestressing, combined with innovative construction methods, were to be seen. In the meantime, the need for repairing and reinforcing existing structures provided the necessary experience and a better understanding of its possibilities.

5.3.1. Structures considered as cast-in-Situ

It was in the framework of structures which may finally be assimilated to cast-in-situ structures, totally built in one sequence only, that the most efficient PT tendon layout was developed.

Indeed, concrete deck structures, incrementally built span-by-span or launched, were initially heavy as PT tendons embedded in the concrete were made continuous by means of expensive couplers or overlapping. The weight of such deck structures having a major impact on the cost of the projects, it was undoubtedly attractive to design these bridge decks with a fully external tendon layout leading to:

- a reduced cross-section area, as there is no tendon in the concrete anymore;
- a better efficiency of the PT tendons, as the area of the cross-section is reduced;
- a PT tendon layout basically designed for the completed bridge while adjustable to the erection method used (Figure 28);

Due to the remarkable fixity of the prestressing line (Figure 29) when the representative tendon layout of the deck is continuous and globally moved from pier to pier, it can be shown that the best tendon layout has to be funicular of a uniform distributed load slightly higher than permanent loads.

It can also be easily demonstrated that trapezoidal tendons, going from pier to pier and simply deviated at third span points, lead to the suitable tendon layout as soon they are funicular of concentrated loads representing 75 % of the uniformly distributed loads mentioned above.
In all of these structures the external prestressing has the remarkable advantage of being continuous in each span, so there is no discontinuity in the prestressing forces, and the structural lightness (generally less than 0.50 m mean thickness) is clearly seen to be a principal characteristic of this type of construction.

Figure 28: Arrangement of external tendons inside the concrete box of an incrementally launched deck

Figure 29: Fixity of the prestressing line
(Any of the representative prestressing line generates the same stresses in the girder)
5.3.2. Segmental bridges built according to the balanced cantilever method

The structures previously mentioned comprise a tendon profile in a certain manner linked to the construction method and not directly transposable to more traditional means, in particular balanced cantilever construction.

However, the simplicity and absence of discontinuity of continuous exposed tendons is a seducing factor for bridge designers and had lead to the development of better tendon profiles than was usual in these structures.

The tendons comprise three families:

- The necessary cantilever tendons, inside the top slab gussets and almost entirely straight
- Some continuity tendons, inside the bottom slab gussets and almost entirely straight also
- A maximum of continuous exposed tendons, placed at the end of construction and anchored at the abutment diaphragms

and these tendon families are found with regularity in the structures built by the balanced cantilever method.

5.3.3. New structures fully prestressed by external tendons

External prestressing also opened up new horizons for geometry, materials and combination of materials.

New structures which may be the "structures of the future" took form thanks to the new degrees of freedom found in external prestressing and more especially in the field of composite steel-concrete structures for which a framework, where the webs are made of thin corrugated steel panels or steel trusses, does not drain axial compressive forces and increase the efficiency of the cross-section in combined bending and axial load.

Many bridges have already been built in this way and all of these examples show how developments in technology and construction methods have been integrated into the construction of economic structures.

![Figure 30: Corrugated Web Bridge](image)

5.4. **External prestressing technology**

Generally speaking, external or exposed prestressing consists of unbonded tendons located outside the structural concrete which could also be called "prestressing stays".
The lack of bond does not mean a lack of quality.

On the contrary, this is a technical solution which has advantages as we will see hereafter. The behaviour of the structures prestressed with external tendons is, if they are properly designed, as good as the classical ones.

There are two families of external multi-strand tendons:

- The non-replaceable tendons (as, for example, the multi-strand tendons placed in a cement-grouted duct)
- The replaceable tendons (as, for example, the galvanised multi-strand tendons).

5.4.1. Cement-grouted non replaceable tendons

These tendons are made of several wires or strands grouped in steel pipes or, more frequently, in straight polyethylene sheaths connected to steel pipes embedded in concrete anchor blocks or deviation diaphragms. All the characteristics of these tendons (pipe diameter, curvature, radius, anchorages) are similar to the traditional tendons embedded in the structural concrete.

5.4.2. Cement-grouted replaceable tendons

These tendons are also made of wires or strands placed inside steel or plastic (High Density Poly Ethylene) ducts able to withstand the grouting pressure.

To be replaceable, therefore dismountable, these tendons must be designed with regard to their replacement:

- The anchorages have to be placed in concrete blocks so that it is possible to have easy access to them
- The typical sheath must be placed in other pipes (with a sufficient diameter) so that the whole cement-grouted tendon can be extracted everywhere it is passing through the concrete.

In these cases the tendon profile must be either straight or perfectly circular:

- Grouting of anchorages has to be easily removable
- Sufficient space for jacks must be provided for tensioning of new cables if any replacement is made

It must be pointed out that the replacement of such external tendons can only be done with destruction of them and it is necessary, prior to cutting external cables injected with cement grout, to take care with regard to safety requirements.

5.4.3. Replaceable tendons protected by a soft material

These cables are made of wires and more often strands necessarily placed in a steel pipe, along the circular parts of the tendon profile, in a steel or a polyethylene pipe elsewhere.

They are protected against corrosion by filling the remaining voids between strands and sheath with grease or wax.
The technology near the anchorages is then a classical one, sufficient place being provided so that the tendons can be removed and if necessary, replaced and tensioned.

5.4.4. Galvanised tendons

Although they are not often employed, galvanised tendons can be used and left unprotected, but then tendon-holding devices must be provided at very short intervals, to prevent damage in case of a strand or cable breaking.

5.5. **Particular problems related to external prestressing**

Problems (or inconveniences) arising from external prestressing are directly related to its simplicity. First of all, the long straight lengths which appear in the tendon profile between diaphragms and anchorages can be at the origin of unsuspected vibrations in the exposed tendons and careful attention must be paid in order to avoid this.

Secondly, the anchorages become increasingly important especially when prestressing is fully external and replaceable.

In this case, the strength of the structure is determined by the resistance at tendon anchorages, and although an isolated incident amongst a large number of tendons is not a danger to structural strength, it is best to try to obtain the highest possible safety factor.

Finally, the abutment diaphragms must be built to resist considerably high and concentrated forces (several thousand tonnes) posing important stability and diffusion problems. Voluminous diaphragms are therefore required.

The technology differs according to whether the tendons are designed to be replaceable or not.

Today, several technological solutions allow replacing of external tendons if necessary. The many advantages which result of such a possibility are at the origin of the development and success of external prestressing worldwide.

**References**

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