Design for maintenance

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Design for Maintenance

Projet de la maintenance

Entwurf der Instandhaltung

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SUMMARY

Road structures are not designed primarily to last for ever ; engineers are trained to adopt profitability criteria as applied in construction. This mentality must change and structures be designed as roads themselves, to function reliably for years to come. This will benefit all, even construction firms, if design is based on correct calculation of costs, understood as the global cost (i.e. construction + maintenance). Design must be reviewed accordingly ; one must choose structures and materials suited to last, and above all, use equipment and accessory works facilitating inspection, substitution of consumables and preventive maintenance. An example of this design-for-maintenance philosophy is the recently built motorway between Carnia and the Italo-Austrian border.

RÉSUMÉ

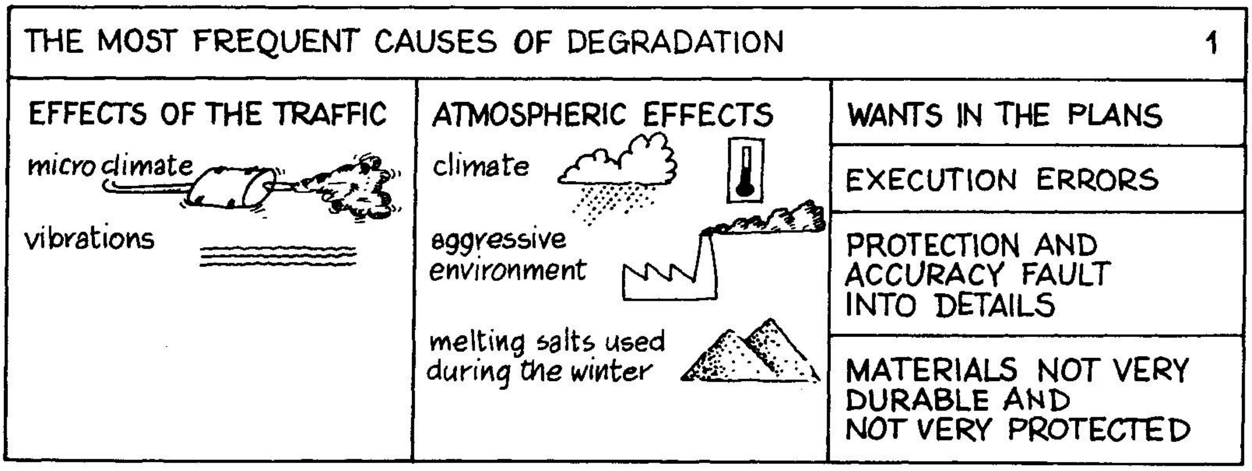
Les structures des routes ne sont pas conçues pour durer éternellement ; les ingénieurs sont éduqués à adopter des critères de profit dans la construction. Cette mentalité doit changer et les structures doivent être projetées comme les routes elles-mêmes, en vue d'une utilisation fiable au cours des années à venir. Cela sera au profit de tous, y compris des entreprises de construction, si le projet est basé sur un calcul correct des coûts, soit le coût global de la construction et de la maintenance. Le projet doit être reconsidéré en conséquence, en choisissant des structures et des matériaux résistants et en utilisant des équipements et des dispositions constructives facilitant l'inspection, le remplacement d'éléments et une maintenance préventive. Un exemple de cette philosophie de projet pour la maintenance est l'autoroute récemment construite entre Carnia et la frontière italo-autrichienne.

ZUSAMMENFASSUNG

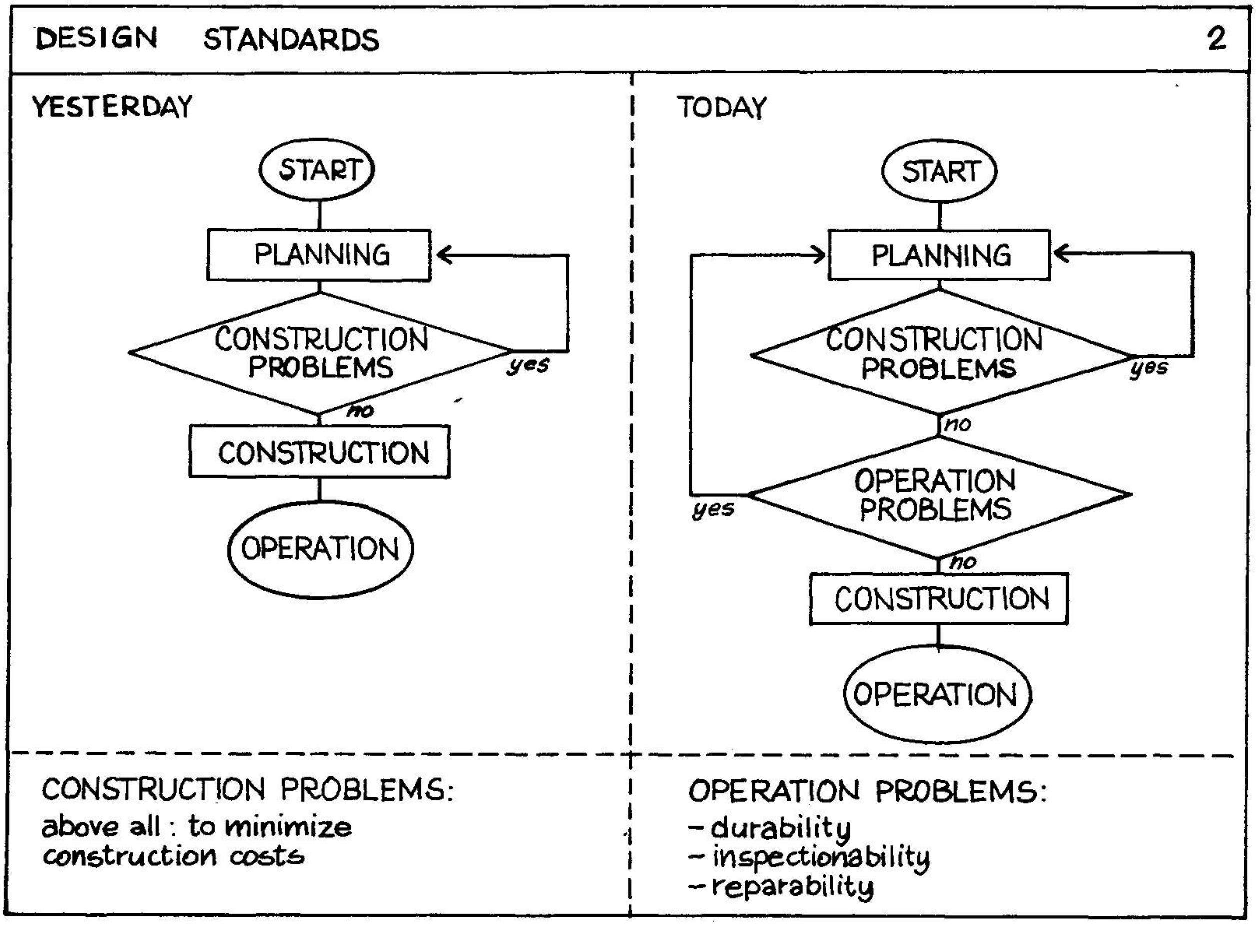
Die Ingenieurbauwerke von Strassen wurden nicht entworfen, um langfristig zu bestehen ; die Ingenieure wurden dazu erzogen, bei der Erstellung von Bauwerken Gewinne zu erzielen. Diese Grundhaltung muss sich ändern, und die Bauwerke müssen nach denselben Kriterien erstellt werden wie die Strassen, nämlich im Hinblick auf eine zuverlässige Nutzung für die Zukunft. Dies wird ein Gewinn für alle Beteiligten sein, auch für die Bauunternehmungen, wenn der Entwurf eines Bauwerks auf einer richtigen Abschätzung der Kosten, der gesamten Baukosten und der Kosten für die Instandhaltung, beruht. Der Entwurf muss entsprechend ausgearbeitet werden unter Berücksichtigung von widerstandsfähigen Tragwerken und Baumaterialien sowie unter Anwendung von Ausrüstungen und konstruktiven Details, welche die Ueberwachung, den Ersatz von Teilen und eine vorbeugende Unterhaltung erleichtern. Als Beispiel dieser Philosophie wird die vor kurzem erstellte Autostrasse zwischen Carina und der italienisch-österreichischen Grenze aufgezeigt.

1. THE MEANING OF A FORMULA

Design-to-maintain is the subject of this note, and the widest interpretation of this summary formula is: design taking into account the durability of the structure as a whole and in its constitutive elements, providing systems to facilitate those repair and maintenance operations which will in any case be necessary.
I would like to dwell for a moment on this last point. It is still all too widely held that road works are intrinsically durable, and when such is not the case, one automatically thinks that they were poorly executed knowingly (with malice). The reality is generally somewhat different; while it is certainly true that road works deteriorate in any case over time (see fig. 1, which summarizes the causes of this phenomenon), it is also true that very often the errors which undermine the durability and maintainability are bound up with the current way the designer thinks, or with his partial view of the problem.



This article and the meeting at which it is to be presented should contribute to changing this mentality, and actually in the course of the last few years there has been an effort to do so. This effort has been generated by the development of road terotechnology, the new science of maintenance which on the one hand defines the special techniques of surveillance and intervention on the different component parts of the road, and on the other provides a series of inputs for the design of new works in such fashion as to foresee and reduce to a minimum the causes of structural degradation, and incorporate devices apt to facilitate maintenance and management.
The designer, on the other hand, as we mentioned, normally has received an education which leads him to give greatest attention to the production stages of the works, i.e. its construction. In fact, in my country, but probably in many others as well, it is the final design which is paid for by the contracting firm, and thus the professional, who works for the firm, tends to optimize all the positive aspects for his direct employer, and hence adopts techniques and equipment which are most valid for his client, but not always up to date or linked to criteria ensuring the durability of the finished works.
Until recently even the shools encouraged "boldness" in solutions, insofar as new possibilities deriving from better understanding of the behaviour of structures and advanced calculation systems were utilized more to reduce the materials used (the famous dead weight, a term which is a program in itself), than to enable it to function with greater durability over time.
Also, the school often does not draw a clear correlation between the training of the structural engineer and that of the materials technologist, which is the basis of the new approach to road structure design.
The consequences of this situation are summarized in fig. 2, under the word "Yesterday". In support of the above, the following table sums up 30 years of



development in Italian motorway construction, divided in periods, types of structures and materials prevalently used.
This evolution has been described many times elsewhere.
Here I would simply recall that at the beginning of Italian motorway construction activity it was not known exactly what types of structures to choose, but decisions had to be made without delay. Each firm proposed what it had done or thought it could do, and each designer gave free rein to his imagination.
Prudence, boldness, banality, geniality: the signs can be seen in those first structures, especially along the customary route of reference, for the Italians, between Bologna and Florence.
Arches, multiple frames, supported beams, cantalevers, continuous beams,... every type is represented and executed with all available materials (except wood).
Those were truly pioneering days (summed up under "1st period" in fig. 3); the majority of the works were constructed with wooden forming constructed on site, but even then we see the first attémpts at industrialization. The centering of the arches, constructed of tubular steel sections for one carriageway, were extended to the second, thus saving a centering (Aglio viaduct, designed by Prof. Morandi); Eng. Zorzi designed and produced the first prestressed beams to be installed (with post-tensioned cables). The economic advantage was immediately evident; following the rule of reducing construction costs, the ten - fifteen years which followed represented the "golden age" of the supported beam: with only minor variations, examples of this type of structure were soon to be found all over Italy ("2nd period" in fig. 3).
But, these bridges were hardly ideal from the standpoint of durability; the many joints characterizing this type of structure are points of entry for degradation agents (in 79% of the cases), and thus the need soon became evident to build with greater attention to durability. Early efforts, maintaining the same

THE MOST USED STANDARDS AND MATERIALS IN THE ITALIAN MOTORWAYS			3
	MATERIALS	STANDARDS	
		isostatic structures	hyperstatic structures
1° PERIOD ('50-'60 YEARS)	REINFORCED CONCRETE PRESTRESSED R.C. STEEL-CONCRETE	RESTED BEAMS (BEARING ON OVERHANG) SPANS < 30 m.	ARCHES FRAMES
2° PERIOD ('60-'70 YEARS)	PRESTRESSED R.C. (ADHERENT WIRES AND POST-STRETCHED CABLES)	RESTED BEAMS SPANS 35÷45 m.	
3° PERIOD ('70-'80 YEARS)	PRESTRESSED R.C. (ADHERENT WIRES AND POST-STRETCHED CABLES)	RESTED BEAMS SPANS 35÷45 m. (ON THE DECREASE)	CONTINUOUS BEAMS CANTILEVERED STRUCT. (DYWIDAG TYPE)

structural types, concentrated on perfecting the joints; originally of rather spartan design, the joint was now divided into two specialized parts, one to provide the waterproof seal and the other to provide continuity to the road surface. Also bridge bearings underwent evolution, as increased efficiency and durability were achieved with the first types of neoprene bearings constructed on site. Starting with brushed-on neoprene vulcanized on site, followed by pot-bearings of encapsulated neoprene, and finally the spherical hinge structures with very low friction sliding surfaces of stainless steel/teflon, there has been an exceptional evolution in these devices, which did not even exist in the earlier bridges or at best amounted to crude metal pieces paid for by the kilogram.

Once the accsessories were perfected, development turned again to the "mature" structure of the motorway bridge: the continuous beam extending over several bays, with movements concentrated on one single point (two, in the case of antiseismic structures), box section, in prestressed reinforced concrete (or more recently in steel concrete, which better resolves the maintenance programming problem), in a structure designed to optimize the global cost (construction + maintenance) of these works which are so fundamental to the existence of the motorway. But typology is only the most apparent aspect of their evolution: protection of the slabs, waterproofing and special pavements, parapets able to contain out-of-control freight vehicles - represent the latest stages in this evolution, together with facilitated inspectability of every "delicate" part of the structure. The future will see the development of global and punctual methods, and ever more sophisticated non-destructive methods to determine scientifically the state of health of the work for maintenance purposes. And what is the guiding element in this evolution? It is simply the increasing determination on the part of the administration responsible for the works that these latter be made more durable, recognizing that the concept of <u>minimizing the global cost</u> (construction + operation) is more valid than that of simply reducing the construction costs.

To do this, however, one must have a strong administration, well prepared to carry out its functions; this means generalist engineers with good management capabilities, able to implement the flow chart shown in fig. 2 under the term "Today" (and I hope also "Tomorrow").

All the concepts set out thus far, even though stated in terms of bridges and viaducts, naturally apply also to all other types of works making up the road (tunnels, pavements, earthworks, etc.).

Let us now attempt to distinguish, again in summary fashion, but in somewhat more detailed manner, the different levels of intervention required in "designing" the maintenance of bridges and viaducts. We have already seen that it is necessary to make decisions regarding:

- <u>type of structure</u> (to resist, but also to last);

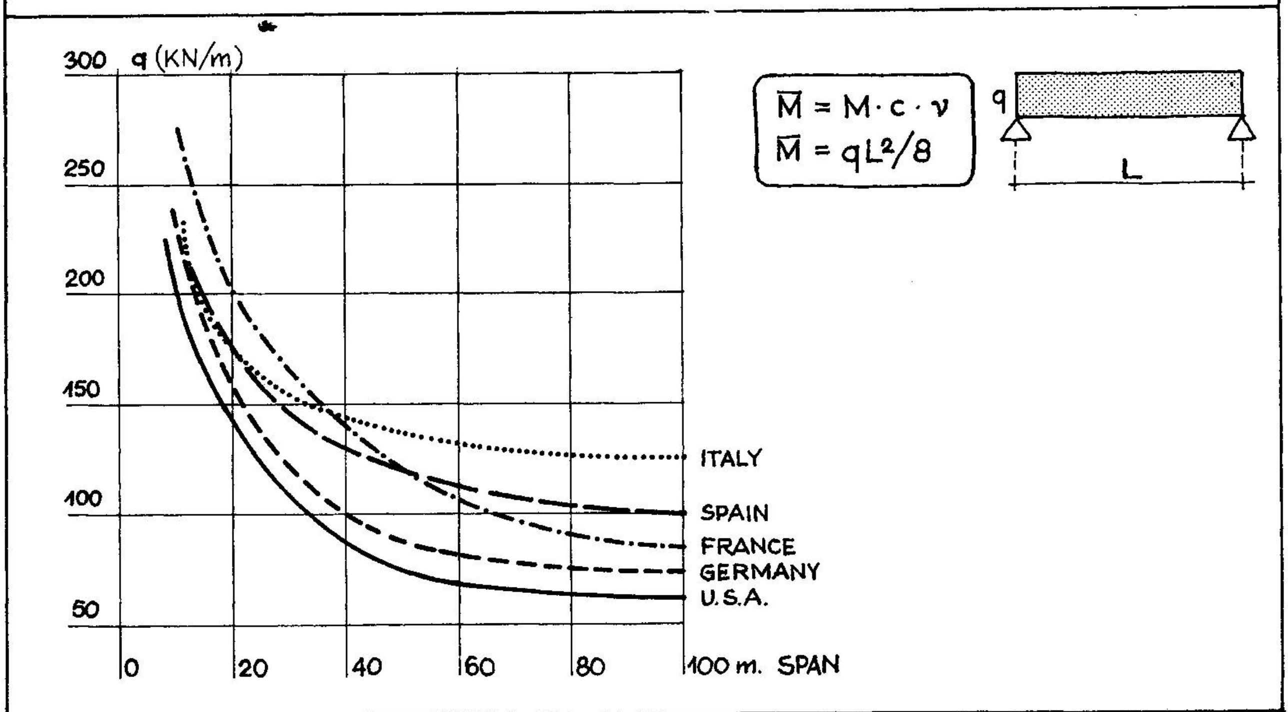
- <u>materials to be used</u> (to construct, but also to protect);
- <u>equipment and accessory works</u> (to function, but also to facilitate surveillance, substitution, etc.).

All of this is aimed at achieving the minimum global cost of the structure; this is a new element, the extra formula to apply when the solution to the problem has not yet been determined. In other words, it is sufficient to choose in such a way that whatever is being built or repaired have maximum operational durability. In fact, even maintenance can be <u>functional</u>, i.e. such as to endow the existing structure with characteristics which it did not have when originally constructed, but would have if it were being built today.
Here we can provide some practical criteria, broken down according to the above three items.

2. SUGGESTIONS REGARDING STRUCTURAL TYPES

The words "structural types" are here understood to mean the various constituent parts of the bridge, i.e. foundations, superstructure, the deck understood as cross-section, and as a complete structural complex. Given the vast range of the subject, it is impossible to give a complete illustation, and it will be necessary to limit ourselves to a few examples intended simply to illustrate the concepts set out in the first section.
To begin with, we must speak of design loads.

DESIGN LOADS (Comparison among different O.E.C.D. countries 4

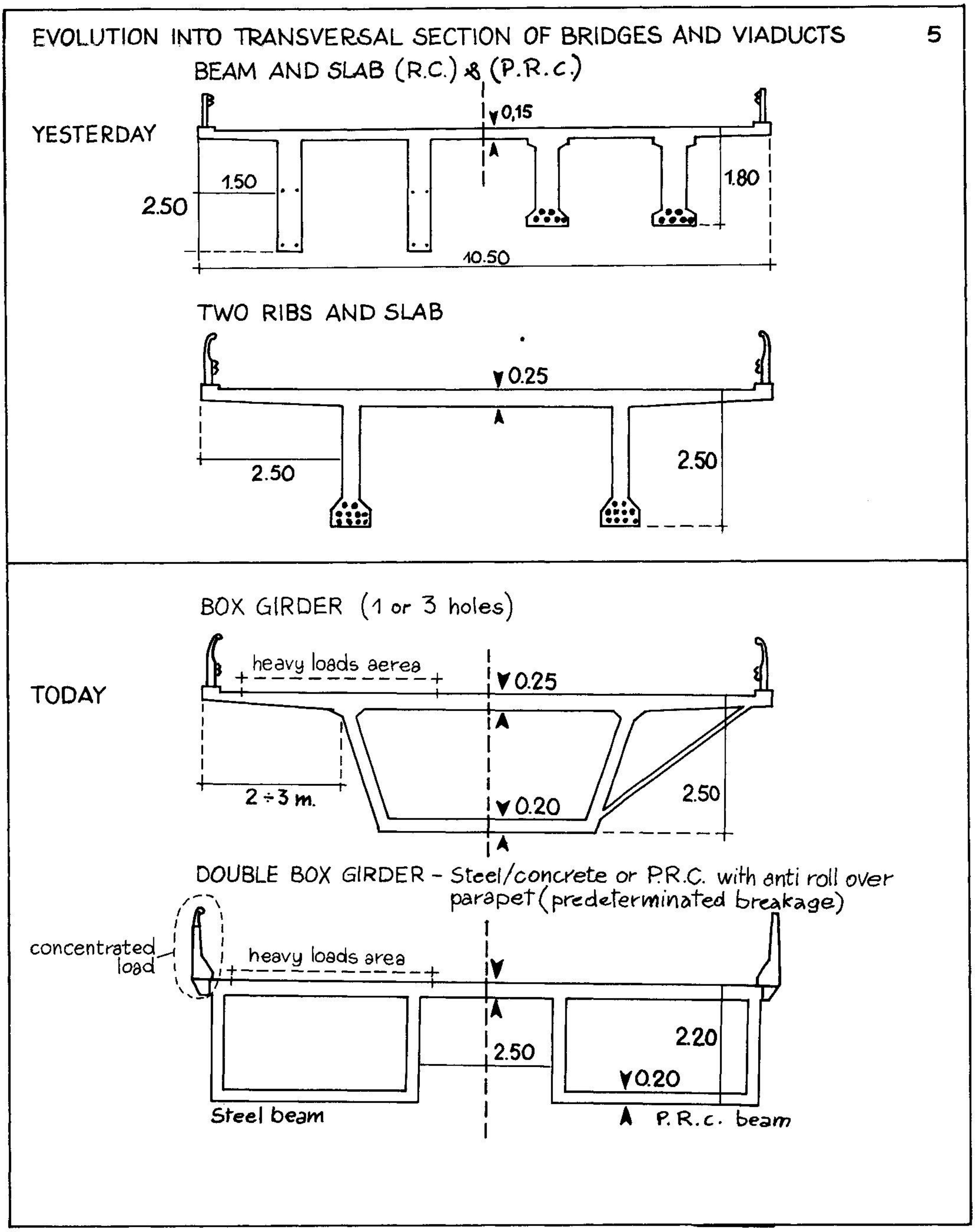


The criterion followed in comparing the various calculation criteria is as follows: start with a simply supported slab (span from 10 to 100 m, width of 7, 11, 15 m); the load is distributed transversally according to the various standards. A hypothetical moment M is calculated, which is derived from the bending moment M_f multiplied by 'C and for V M = M_fC V where C is the dynamic allowance and V is the ratio between the σ of the start of the permanent deformation and the σ allowable in the steel rods. M is then divided into a uniform load q (in KN/m) according to the expression $q = 8M/L^2$. The figure shows one of the diagrams obtained.

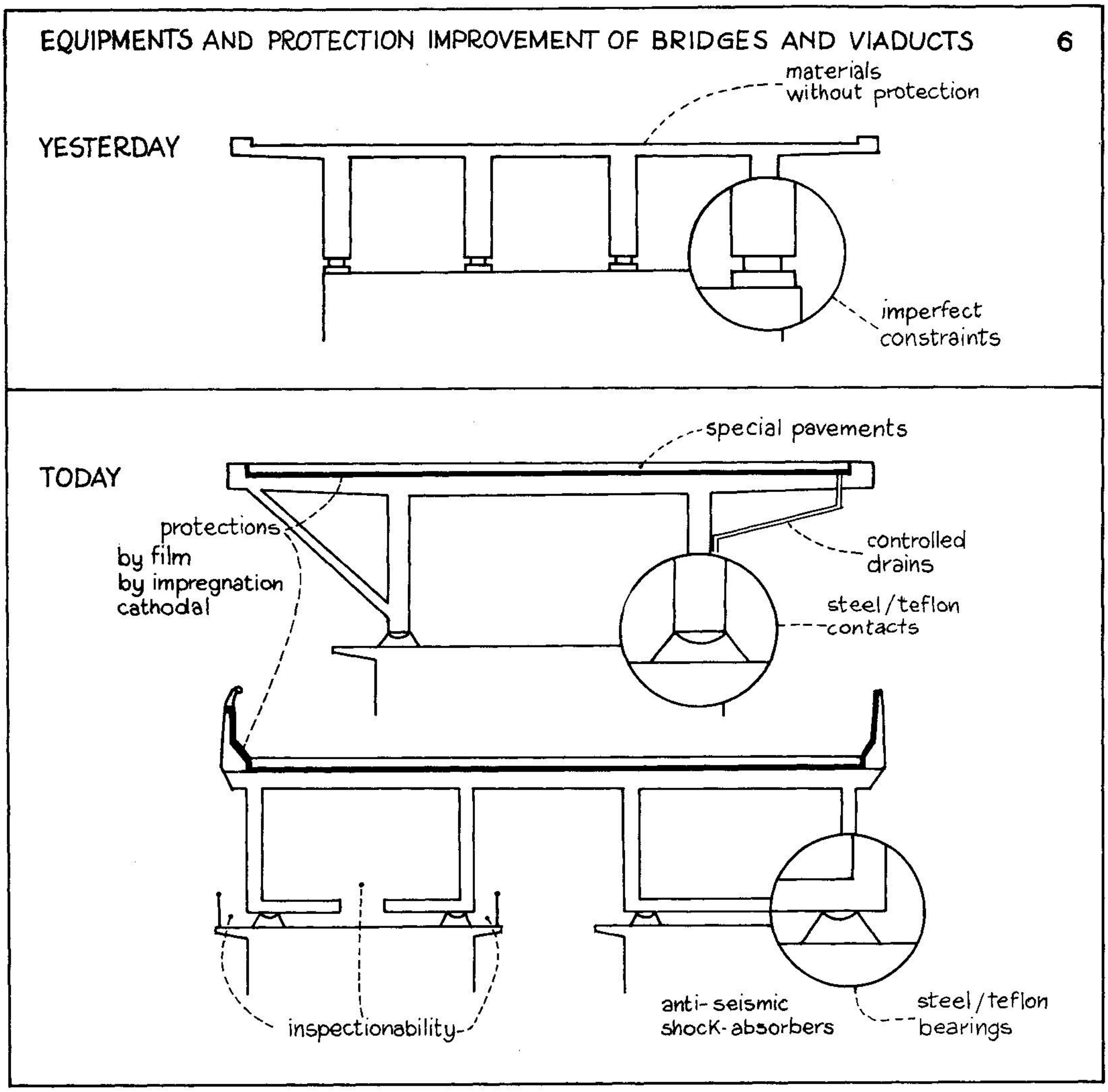
In this regard it is interesting to note that the greater or lesser probabilities of degradation of a structure are linked closely to the greater or lesser initial over-sizing. In fact, it we examine the magnitude of design loads, their transversal distribution, the varying degree of simultaneous presence on the structure and the different dynamic coefficients prescribed in the various countries, we can draw some interesting conclusions.
In a study conducted by the OECD on the bearing capacity of bridges, such a comparison was attempted, using a schematization of the design loads; the results are shown in the diagram in fig. 4.
One can see how the Italian standards (for bridges already constructed) are rather limiting, especially as far as regards structures with spans exceeding 30-35 m.
In countries such as the United States and Germany, on the other hand, the design loads are much more contained, and this leads inevitably to the construction of "lighter" structures. The reason may lie in the tendency in these countries to consider the period of service, i.e. the working life of the structure, as limited in time, in a pre-established manner.
Certainly this approach contrasts with the tendency to minimize the weight of the structures and to consider in their design only the true loads which will act upon them, but by using loads greater than those which would have acted on the structure, one thus corrects (and can still correct) many "errors" or unforeseen developments (increase in loads transported, in transport speed, etc.).
I will not dwell on the matter of foundations; it is sufficient here to recall that today it is possible to avoid costly repair interventions through judicious use of large diameter piles and well-type foundations, depending on the soil and the problem to be resolved. Accurate prior hydrogeological studies permit the design of suitable protection so as to prevent erosion when constructing works in river beds; also in this case it is strictly necessary that the work of the structural engineer be complemented by that of another expert, the hydrogeologist.
The most obvious typological development in the design of bridges for durability is in the bridge deck, the part in most direct contact with the live loads, which represent the essential reason for the structure. I have attempted to outline the evolution and thus the trends regarding future designs in the two figures 5 and 6 below, even though these deal more explicitly with the cross-section and equipment rather than strict typology.
Caisson structures are substituting those made up of series of flanking beams; this facilitates inspectability and improves performance under load. As mentioned, the use of these structures on continuous beams has led to development of the most durable and reliable typology thus far conceived. Also the type of traffic envisaged today has prompted the move to caissons which differ in shape from the traditional trapezoidal form with wide wings; the trend is to adopt the triple caisson center plus wings, as employed on the Carnia motorway, where the greater thermal insulation provided by this type of cross-section and the reduction of lateral action of the cold winds due to the presence of the continuous guardrails, renders winter freezing conditions more homogeneous on the pavement surface, and improves traffic safety.
In the new design of the Bologna-Florence motorway, we will employ a double caisson positioned under the zone travelled by freight vehicles, as well as anti-rollover guardrails designed to contain large trucks, being of such weight (from 875 kg/m up to 1100 kg/m in the two versions from 1.47 m to 1.70 m in height) as to be able to sustain the maximum impacts envisaged.

3. MATERIALS TO BE EMPLOYED

This is the sector which in my opinion has seen greatest development and presents the widest range of possibilities and implications with regard to designing for durability. It has been a quiet revolution, often overlooked by the



structural designer, even though the more advanced criteria for strucural reliability are always more closely linked to the real strength characteristics of the materials used in the works.
Here I cannot supply more than a simple and incomplete list; it is necessary to consider two major categories:



- materials which serve in the construction of the structures;
- materials which serve for the protection over time of the former.

The more advanced tendency among designers is to choose materials which combine the two characteristics mentioned above, but this is not always possible.

My opinion, in all cases, is that it is better to "overdo it" in the matter of protection.

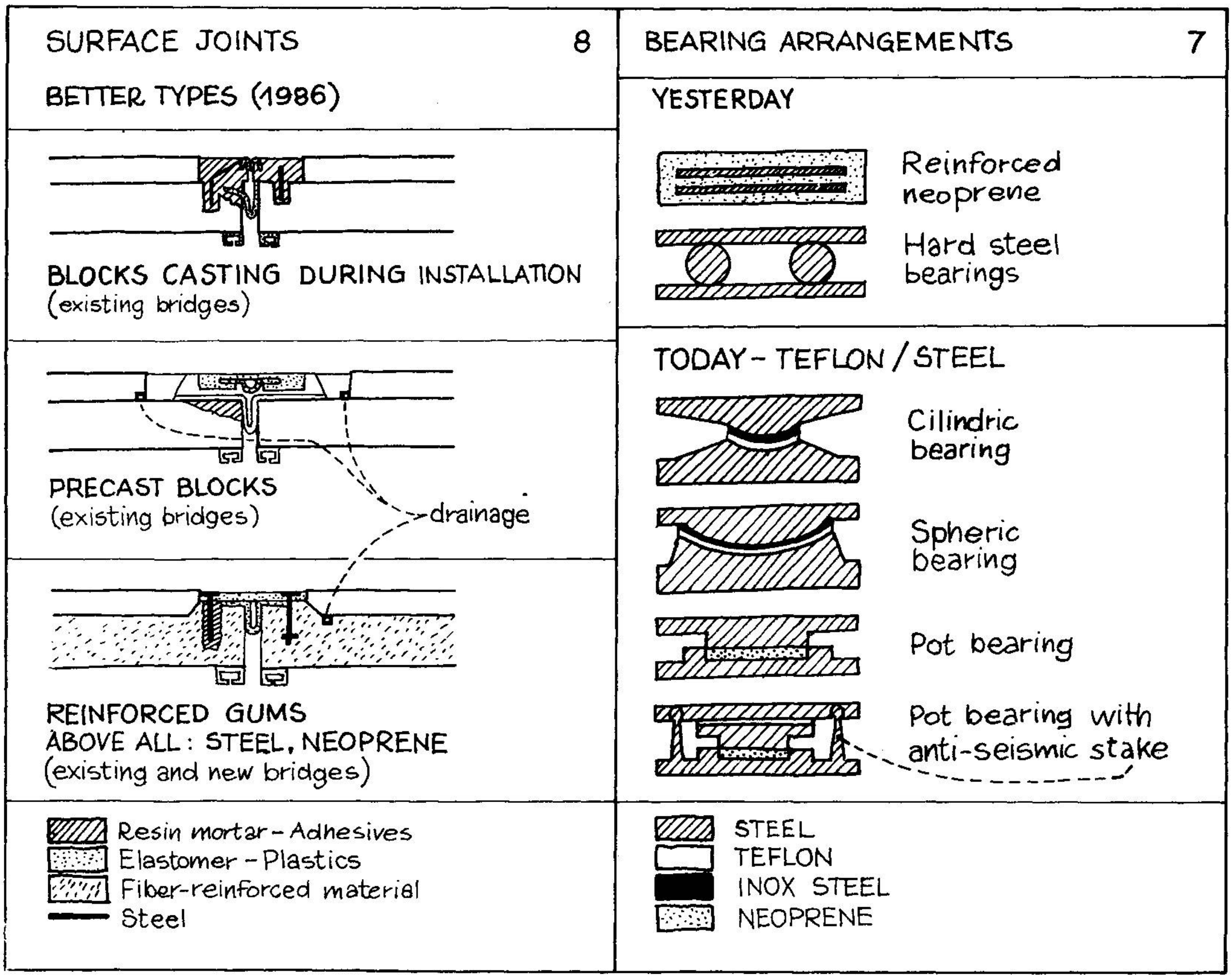
Of the various self-protecting and structural materials, I would first mention concrete with low water/cement ratio and high workability, in certain cases also non-shrinking (in Italy we call it "rheoplastic non-shrink cement"; our technical standards include concretes which must satisfy not just certain strength characteristics, but also durability prescriptions with indications of the types of cement and the water/cement ratio (w/e 0.42 and slump 18 cm). In parentheses I have indicated the values for class 1 - maximum durability. These can be obtained with superfluidizers and foamer additives.

The first category should also include the highly protected prestressing steel (in bars or toroids) coated with epoxy resin films. These permit resolving the most common problem for maintenance design: the generalized use of cathodic protection also for works in prestressed reinforced concrete. The reason why

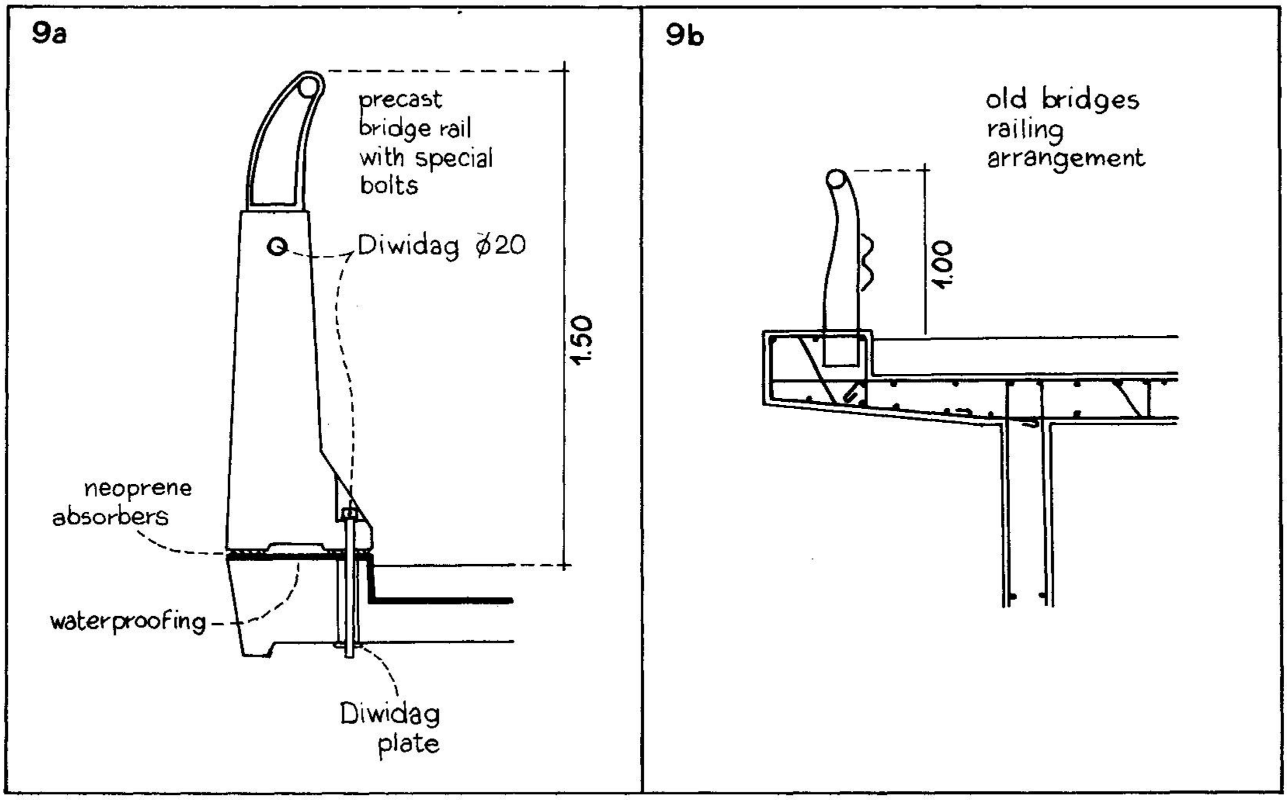
protection also for works in prestressed reinforced concrete. The reasón why this material is so important in prestressing is that the great development of protective materials (used mainly in slabs) has led to a rise in costs in this sector. Preparing a durable concrete, impregnating it with resin after pouring, then waterproofing it with synthetic polyurethane film and finally covering it with a durable and non-deformable pavement under these conditions (with the water remaining in it because it cannot drain rapidly through the waterproofed deck) costs at least as much as a sound active cathodic protection of the reinforcing steel. This latter procedure, however, generates nascent hydrogen during operation, which in turn may attack the prestressing steel.
Thus in order to have good protection, one must either avoid prestressing, or protect the prestressing steel from the H^+.
One of the most insidious enemies of durability, however, is the carbonation of the cement overlay, which in a matter of a few decades can destroy the protective concrete envelope around the reinforcing steel.
Possible solutions include corrosion inhibitors (calcium nitrites, $Ca(NO_2)_2$) in the casts, the use of microsilicates, ("silica fume" derived from steel processing), protective paints and also, of course, rheoplastic concretes. Each of these materials merits a discussion apart, and in any case one can truly say that there are too many to choose from.

4. EQUIPMENT AND ACCESSORY WORKS

These are the consumable parts of the works, and also here there have been significant developments such that I will limit myself to a simple list.
In the case of bearings (fig. 7), steel/teflon has had very rapid development.



Problems have been encountered in works affected by severe traffic vibrations due to the accelerated "chewing" phenomenon (consumption linked with very small but rapid oscillating movements, and not due to the larger, slower expansion/contraction movements).
There has also been great progress in counteracting seismic actions (on both new and existing bridges). The more advanced devices (in fact, of recent days) contain steel hinges which yield under the actions of an earthquake (but in the direction and with the forces desired); these were developed out of neoprene and lead bearings used in New Zealand.
Joints have reached a stage of stability, with the widespread use of neoprene/steel devices on reinforced concrete blocks, which in most recent installations have also been reinforced with fibre (the full name is rheoplastic, sulpho-resistant, fibro-reinforced anti-shock joints)(see fig. 8) But the most recent developments on which full-scale tests are just now underway have to do with the anti-rollover, double-duty (against both cars and trucks), prefabricated bridge guardrail (see fig. 9). Also in this case we have an innovation concealed under a traditional form: the system of attachment to the bridge deck and of resistance to collision is designed and calibrated in such a way as to avoid transmitting excessive forces to the bridge structure itself (the impacts of trucks may reach 75 to 100 tonnes, even though only for microseconds). The



impact strength of these devices is a mixed function of beam and bracket, based on a dywidag ∅ 20 horizontal bar and attachments, of a strength varying according to the reinforcing present in the structure, at the foot of the wall, which has a New Jersey profile. An additional steel handrail or the wall itself extended to a height of 1.70 m from the road surface comprises the upper part of the structure. In cases of collision, maintenance is immediate, as the element can be replaced in minutes.

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