Active Control of Bridge Structures

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To be Presented at –

MARAS – 91, Southampton, April 1991

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Trumpington Street
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December 1990

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ABSTRACT

The paper describes a possible replacement for the traditional 'Bailey Bridge' type of structure. The system consists of Vierendeel Truss panels, which can easily be joined together, and minimises the secondary moments normally associated with such trusses by the use of an actively controlled prestressing system.

Straight prestressing tendons pass from end-to-end of the structure along the mid-line of the Vierendeel panels, and long stroke jacks are connected between the tendon and the top joints between the panels. As a load passes over the bridge, these jacks are extended to counteract the bending effects within the panels, and to increase the force in the prestressing tendon, thus ensuring that the trusses are subjected to primarily axial forces and that all joints remain closed.

The requirements of such a system to deal with large moving loads are considered, such as might be encountered in military applications or as temporary works on site. The case of a 25m span bridge carrying a 100 Tonne HB-type vehicle at a speed of 0.25m/s is considered to determine the requirements of the mean prestressing force, jack stroke and hydraulic power capacity. The principles of the control system are considered, as are the nonlinear effects of the varying inclination of the jacks and the large deformations of the prestressing tendons.

INTRODUCTION

Structures are traditionally regarded as carrying their load in a fixed manner. The distribution of dead load forces is controlled by the erection sequence with, in special cases, redistribution being induced at that time by the application of prestressing forces to stays or cables, or by jacking at the supports. The live load distribution is simply that which results from the normal behaviour of the structure; the only control that the designer exerts over the distribution comes from the relative sizing of the members.

The implications of this are so fundamental to normal structural design that they pass unremarked by most engineers, but the effect is that structures have to be designed for the maximum range of loads that can be applied throughout the life-time of the structure. The penalty in terms of weight and cost can be large, especially in structures in which the extreme live load forms a high proportion of the total load on the structure.

The use of active, or reactive, structures, which change their configuration in response to the applied loads, offers a way of overcoming that inefficiency, but at the penalty that the fixed structure becomes a machine, with all the attendant difficulties of control and maintenance. Certain types of structures conventionally have maintenance personnel in attendance; these include large structures, such as major river crossings, and temporary bridges, such as those used by the military or civil engineers. It is to this last class of structures that this paper is addressed.

It is perhaps worthy of note that not all 'structures' have evolved in the conventional way. The function of many of the muscles in animal and human bodies appears to be to reduce the stresses in bones [1]; the resulting costs in terms of muscle fibre, control mechanisms and energy have presumably been found to be made worthwhile, in evolutionary terms, by the consequential reduction in bone size that this allows.

The work presented here is largely the result of a third year project [2] carried out at Imperial College, inspired by ideas from Prof Sir Alan Harris, and his contribution to this work, and his permission to publish this paper in this form, are gratefully acknowledged.

STRUCTURE USED IN DESIGN EXAMPLE

The structure used as the basis for this study is a demountable Vierendeel truss bridge, with a span of 25m, designed to carry an HB vehicle of total weight 100 Tonnes. This load is assumed to be evenly distributed on 4 axles, with spacings of 1.8m, 6m and 1.8m. For calculating the power requirements of the system, it is assumed that this vehicle is travelling fairly slowly (0.25m/s = 0.5mph). This is probably reasonable given that such a large load would be under fairly careful control while crossing a bridge of this type. When presenting results which depend on the position of the vehicle on the bridge, the position of the *centre* of the vehicle will be given, measured relative to the left hand end of the structure. Thus, some part of the vehicle will be on the bridge with this position varying from -4.8m to 29.8m. The vehicle is assumed to be travelling from left to right on the bridge, in cases where the order of application of the forces is important.

The prestressing tendon is assumed to be a Type G Parafil rope, which consists of a core of high modulus (126kN/mm^2) Kevlar 49 yarns, contained within a polymeric sheath. The design strength of such tendons (1930 N/mm^2) compares well with conventional steel tendons, and there are advantages such as light weight and resistance to corrosion which would be important in a demountable structure. Such tendons are now being widely considered for use as prestressing tendons in concrete structures [3], and also as stay cables in bridge and tension structures [4]. Although the numerical results would be slightly different if steel tendons were used in the present case, the broad conclusions relating to active prestressing would be unaffected.

A conventional, unprestressed, Vierendeel truss is shown in Figure 1. It is arranged as a series of 10 identical panels, each 2.5m long and 2.0m high. The panels are arranged in pairs, on each side of the roadway, and adjacent panels are joined together by means of shear pins in the top and bottom chords. A simplified analysis shows that a rectangular hollow section 150*150*66.4kg is adequate for the unprestressed structure.

Figure 2 shows the same structure with the addition of a prestressing tendon running between each pair of trusses. The tendons are anchored at the centre of the vertical posts at each end of the bridge (so 'K' bracing is required in the outer panels), and is connected to the top chord of the structure by means of hydraulic jacks which act on the shear pins joining adjacent panels. Figure 3 shows a perspective view of one bay, with the jacks removed for clarity.

The same member dimensions have been assumed for the analysis of the prestressed structure as were used for the conventional structure. In practice, a reduction in member weight would almost certainly be possible.

The prestressing tendons are 87mm diameter Parafil ropes, which have a core area of 4400mm^2, and a breaking load of about 850 Tonnes. It is assumed that each tendon has an initial prestress of 160 Tonnes. These figures have been obtained on the basis that the deflection of the tendon below the neutral axis under live load is to be limited to about 40% of the depth of the truss.

The jacks connecting the tendon to the top chord need to have a capacity of about 80kN, with a stroke of about 0.8m. These figures are well within the capacity of jacks used in hydraulic excavating machines, so there would be no difficulty in obtaining such equipment.

The bottom chords of the trusses are joined at roadway level by cross beams. Decking units (whose design is not considered here) are assumed to rest on these cross beams, so no load is transmitted to intermediate positions along the length of the bottom chord members.

BEHAVIOUR OF THE UNPRESTRESSED SYSTEM

The analysis of the bridge in its unprestressed configuration has been carried out on the assumption that the shear force in each panel is equally distributed between the top and bottom chords, and that there are points of contraflexure within each panel at the mid-point of both the chords and posts. This effectively assumes that the posts are rigid when sharing the shear forces between the top and bottom chords, but the error will be small.

On these assumptions, the structure takes up a complex deformed shape (shown exaggerated in Figure 4), with clear local bending in both the chords and the posts. The maximum global bending moment on a single truss (i.e. one of four), is 1055kNm, and the maximum shear force is 123kN, under the action of the 100 Tonne HB vehicle.

ACTIVE CONTROL SYSTEM

The aim of the active control system will be to relieve the Vierendeel truss of as much of the secondary loads as possible. This will be done by extending the jacks to exert upwards forces on the top chord joints that counteract the downwards loads being applied to the bottom chord through the cross beam. To that end, the system must comprise:-

(a) a sensing system which determines the forces to be applied,

(b) a computation unit to evaluate the appropriate action to be taken, and

(c) a servo mechanism to control each jack.

The sensing system is most logically provided by monitoring the difference in the shear force between two adjacent panels, which can be obtained by measuring the difference between the local bending moments in the chords of the truss. The difference between strain gauge readings from the top and bottom surfaces of the horizontal chord members would give the local bending moment in that truss, and the difference in moment between two adjacent panels would be proportional to the required applied force.

The computation unit could be very simple, and would not need to be a digital system, since analogue readings of the strain gauges could be used directly. However, it might be sensible to feed the results through a computer system of some sort to monitor the behaviour of the system and to provide some sort of redundancy in the event of failure of one of the gauges.

The servo-control mechanism for the hydraulics would be standard equipment, so there would be no special requirements for that system. The system would, however, have to control the *pressure* in each jack separately, and allow flow of oil into or out of the jack to maintain that pressure. As will be shown later, there will be occasions when the force in the jack is increasing while the flow of oil is back towards the pump; this occurs when the structure is unloading after the passage of a vehicle, and the energy stored in the prestressing tendon is being passed back to the jacking system.

STATIC ANALYSIS OF THE PRESTRESSED SYSTEM

The method of analysis adopted to determine the behaviour of the prestressed system considers the truss and the cable separately, linked together by the forces in the jack. The analysis of the truss itself, under the action of the active prestressing force is not significantly different from the unprestressed case, since all the loads are applied to the truss through the node points, and the deflections are small so there are no difficulties with non-linear effects. However, the behaviour of the tendon is more complex, and since deflections of the order of 1m are being considered, non-linear effects must be taken into account.

The analysis must allow for:-

(a) the inclination of the tendon to the horizontal,

(b) the eccentricity of the tendon from the neutral axis of the structure,

(c) the inclination of the jack to the vertical, which results in some horizontal forces being applied to the truss, and

(d) the axial stiffness of the tendon.

It is assumed that there is no slip between the jack and the tendon, that the jack is free to pivot about its point of attachment to the top chord, and that the response of the jacking system is instantaneous. The implications of this last assumption will be considered later in terms of the power requirements for the hydraulic system, and the response time of the control system.

Consider the system in Figure 5.

At each clamp (e.g. A), vertical equilibrium gives

$$T_i \sin\alpha_i - T_{i+1}\sin\alpha_{i+1} - P_i\cos\gamma_i = 0$$

while horizontal equilibrium gives

$$-T_i\cos\alpha_i - P_i\sin\gamma_i + T_{i+1}\cos\alpha_{i+1} = 0$$

and geometrical compatability gives

$$d_{i+1}\cos\gamma_{i+1} - d_i\cos\gamma_i = \{a + d_i\sin\gamma_i - d_{i+1}\sin\gamma_{i+1}\}\tan\alpha_{i+1}$$

The force in the tendon can be related to the geometrical changes by

$$\frac{a + d_i\sin\gamma_i - d_{i+1}\sin\gamma_{i+1}}{\cos\alpha_{i+1}} = \left[\frac{1 + \frac{T_{i+1}}{EA}}{1 + \frac{T_0}{EA}}\right] a$$

By setting up a set of equations of this form, and specifying the vertical component of the force in each jack, a set of non-linear simultaneous equations is produced, which can be solved by any suitable method, such as multi-dimensional Newton Raphson iteration.

BEHAVIOUR OF THE PRESTRESSED SYSTEM

The cable profile, for the vehicle in 7 different positions, is shown in Figure 6. Maximum cable deflections of about 0.76m occur with the vehicle near midspan. The force in each tendon increases from its initial value of 160 Tonnes, up to a maximum of 286 Tonnes; the total tension force is about 5.8 times the weight of the vehicle, which is fairly typical for prestressed concrete bridges. Both the top and bottom chords of the truss are in compression, with most of the bending being carried by the cable.

The jack forces do not completely cancel out the bending moments and shear forces in the bridge, since the jacks pivot about the top chord of the bridge, while the load is applied to the bottom chord. These effects are small, and most of the local bending moments associated the Vierendeel trussses are eliminated.

The stroke of the various jacks (measured from the top node), is shown on Figure 7, against the position of the centre of the vehicle, while the force variation in one jack (jack 3), is shown in Figure 8. From these figures it is clear that the control system, which would be controlling jack force, would need to be able to allow the jack extension to vary at the same time, since the cable profile would be affected by the actions of the other jacks.

The total power requirement for each jack can be calculated by considering the movement of the jack and the force in the jack, and the results for jacks 1-5 are shown in Figure 9. The power scale needs to be multiplied by the vehicle speed to get true power; the figure also relates to the jack power applied to each half of the truss. For these jacks, which are to the left of the mid-span region, net positive work is done by the jacks as the vehicle moves on to the bridge, while only a small amount of the work is recovered as the vehicle moves off. However, for the corresponding jacks on the other side, the situation would be reversed, and the total amount of work done in the bridge as a whole should, at least in theory, be recoverable.

This observation leads to the intriguing prospect that a power pack could charge up a hydraulic accumulator, which could be used to power the jacks; suitable one-way valves could then be used to recharge the accumulator as the vehicle moved off the bridge. This system would be energy efficient, but more importantly, would not need a large source of hydraulic power. However, the design of the hydraulic system, and also the control system, would need to be carefully worked out in detail.

One important parameter for the design would be the rate of application of the jack force. This is dependent on the speed of the vehicle; the maximum rate of loading in any one jack is about 31.4*v kN/s, where v is the speed of the vehicle. For v = 0.25 m/s, the maximum power requirement in any one jack is 3.25 kW. However, not all jacks would be requiring power at any one time, as can be seen from Figure 9, so the jacking system would not need to power all 18 jacks simultaneously at this rate.

TIME DEPENDENT CONSIDERATIONS

The system described so far is capable of effectively transferring the whole load of the heavy vehicle to the cable, while the actual bridge structure acts as a reaction frame under axial force and distributes purely local loads. However, there are two principal time dependent effects that need to be taken into account in a practical application. There will be a delay between monitoring the out-of-balance shear forces in adjacent panels, and applying the required correcting force. Similarly, in a real situation, the vehicle may not cross at a speed that the pump system can cope with.

Two numerical simulations have been carried out to illustrate these points. In each case, the vehicle speed, the sampling interval and the force capacity (expressed as a maximum change in jack force per second) are specified. The following procedure has been adopted:-

(a) The difference in the shear force in adjacent panels is calculated.

(b) The desired new force to be applied at the next time step is determined.

(c) If the jack force capacity is high enough, this force is applied to the system. If not, the maximum force change that the system can apply is determined, and this value used instead.

(d) The new cable profile, and the corresponding force distribution in the truss, at the next time step are then calculated.

The whole process is repeated for the complete passage of the vehicle. The response of the system lags behind the requirement, and is thus *reactive*. No attempt has been made to build predictive elements into the system, which would make the system truly *active*, although it should be possible to refine the model to make it predictive, especially for a structure carrying one-way traffic.

Effect of varying sampling interval

A simulation has been carried out with the following parameters:-

Vehicle velocity : 0.25 m/s
Sampling interval : 0.5 s
1.0 s
2.0 s
4.0 s
Jack capacity : 15 kN/s

Figure 10 shows the resulting bending moment in the truss for one position of the vehicle (at 17.5 m), for the different sampling intervals chosen. This position is the worst position for out-of-balance forces, since it corresponds to the position where the vehicle axles start to move off the structure. At an interval of about 0.5 s, the maximum bending moment is about 20 kNm, which increases to about 100 kNm at 4.0 s. These should be compared with a maximum bending moment of 1055 kNm in the unprestressed structure.

Effect of increasing vehicle speed

A second simulation has been carried out varying the vehicle speed.

Vehicle velocity : 0.125 m/s
0.25 m/s
0.5 m/s
1.0 m/s
Sampling interval : 1.0 s
Jack capacity : 15 kN/s

At 0.5 m/s, the speed just about matches the jacking capacity, but at the faster speed, it is to be expected that the system will not be able to respond sufficiently quickly. This is illustrated in Figure 11, which again shows the bending moment in the truss. The response is reasonable if the vehicle is travelling at lower speeds, but once the capacity of the bridge to respond is exceeded, the bending moment increases dramatically, reaching about 270 kNm in the worst condition (illustrated in the figure).

Changing the speed of response of the system would have a small impact on reducing the bending moments for the slower vehicles, but for the faster vehicle, where the response of the system is governed by the rate at which the jacks can apply force, no such improvement could be made.

LIMITATIONS OF THE ANALYSIS

The analysis presented here is limited. The truss has been considered as a two-dimensional structure, and detailed design of the flooring system has not been carried out. No attempt has been made to redesign the truss to take advantage of the reduced bending moment in the system, nor has detailed design of the hydraulic system been undertaken.

The absence of these considerations, however, does not invalidate the principles described here. The idea of measuring shear forces in adjacent panels of a Vierendeel truss, and minimising these by applying upwards forces to the structure which are reacted against a prestressing cable, remains valid.

CONCLUSIONS

The paper has demonstrated that active control of bridge structures offers a way of enhancing the load carrying capacity of the bridge. All of the techniques described in the paper make use of existing technology, although their combined application to this type of problem may be new.

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