APPENDIX I

A PROOF OF THE THEOREMS OF CASTIGLIANO

THE following proof of the theorems is in its method essentially the same as that given by Professor Föppl in his "Technische Mechanik." Let a number of forces (or moments) P's be simultaneously and each gradually applied on an elastic body, making corresponding displacements (or rotations) y's.

Since the internal work equals the external work, we at once have

$$\omega = \tfrac{1}{2}\Sigma Py,$$

ω denoting the amount of internal work.

Suppose now that one of the forces, say P_v, is a variable one, and receives a uniformly varying increment dP_v, which will be assumed to attain its ultimate amount simultaneously with P_v; then, since each y is a certain function of P_v, we have for the first derivative of any one term Py with respect to P_v,

$$P\frac{dy}{dP_v},$$

and so for all other terms, except $P_v y_v$, as P_v and y_v are both variable quantities.

For this we have

$$\frac{d(P_v y_v)}{dP_v} = \frac{P_v dy_v + y_v dP_v}{dP_v} = P_v\frac{dy_v}{dP_v} + y_v.$$

Summing up the results, we get

$$\frac{d\omega}{dP_v} = \tfrac{1}{2}\Sigma P \frac{dy}{dP_v} + \tfrac{1}{2} y_v \quad . \quad . \quad . \quad . \quad . \quad (a)$$

If, on the other hand, we suppose the body in the first place to be acted on by all the P's and to these dP_v to be subsequently added, the ultimate amount of the ω will be the same as in the preceding case. In the present case, the gradual application of dP_v changes y of any one force P by dy with respect to P_v, whereby the force which remains constant performs the work

$$Pdy,$$

and so with other forces including P_v.

The work performed by dP_v itself amounts to

$$\tfrac{1}{2} dP_v dy_v.$$

As this latter, however, is a quantity of the second order, we may neglect it in comparison with the increment of works performed by the forces themselves, and put

$$\frac{d\omega}{dP_v} = \Sigma P \frac{dy}{dP_v} \quad . \quad . \quad . \quad . \quad . \quad . \quad (b)$$

Combining equations (a) and (b) we get

$$\frac{d\omega}{dP_v} = \tfrac{1}{2}\Sigma P \frac{dy}{dP_v} + \tfrac{1}{2} y_v = \Sigma P \frac{dy}{dP_v},$$

from which

$$\frac{d\omega}{dP_v} = y_v,$$

which proves the first theorem.

The second theorem is, as already explained, a special case of the first one, and is at once deducible from the latter.

APPENDIX II

TEMPERATURE STRESSES IN VIADUCT BENTS

(Being a supplement to Chap. II)

THE temperature stresses in an ordinary viaduct bent are often not possible of combination with stresses arising from other causes, unless the temperature at the time of erection is exactly known. The following discussion concerns the stresses produced by any given change in temperature alone.

Let

t = the range of a temperature change;

θ = coefficient of expansion and contraction.

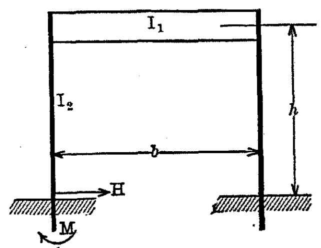

Fig. 1

Then in the bent of Fig. 1 a rise of t above an initial temperature would increase the distance b between the posts by $t\theta b$ were the latter free to move.

However, the lower ends of the posts being assumed to be firmly fixed, moment and horizontal reaction would be produced at each end; each horizontal reaction H acting, as it were, through a distance of

$$\frac{t\theta b}{2}.$$

Calling the moments producing compression on the outside fibre of the frame positive, we have for the bending moment at any point in the post,

$$M - Hx,$$

and in the cross-girder,

$$M - Hh.$$

Then, neglecting the effect of direct stresses, we get for the internal work in the frame,

$$\omega = \frac{1}{EI_2}\int_0^h (M - Hx)^2\,dx + \frac{1}{2\,EI_1}\int_0^b (M - Hh)^2 dx$$
$$= \frac{h}{EI_2}\left(M^2 - HMh + \frac{H^2h^2}{3}\right) + \frac{b}{2\,EI_1}(M - Hh)^2,$$

in which I_1 and I_2 denote the moments of inertia of the cross-girder and posts respectively, and E the modulus of elasticity of the material.

Then, according to the principles of work,

$$\frac{d\omega}{dM} = 0, \qquad \frac{d\omega}{dH} = t\theta b.$$

So that we at once get

$$\frac{h}{I_2}(2\,M - Hh) + \frac{b}{I_1}(M - Hh) = 0,$$
$$\frac{h}{3\,I_2}(3\,M - 2\,Hh) + \frac{b}{I_1}(M - Hh) = -\frac{Et\theta b}{h},$$

from which

$$H = \frac{2\,hI_1 + bI_2}{h\,(hI_1 + bI_2)}\,M,$$
$$M = \left(\frac{hI_1 + bI_2}{hI_1 + 2\,bI_2}\right)\frac{3\,EI_2 t\theta b}{h^2}.$$

In case the lower ends of the posts are hinged, $M = 0$, so that we get

$$H = \left(\frac{3\,I_1 I_2}{2\,hI_1 + 3\,bI_2}\right)\frac{Et\theta b}{h^2}.$$

Referring to the numerical example given on page 27, for

$$t = 50^\circ \text{ Fah.},$$
$$\theta = .000007,$$
$$E = 30{,}000{,}000 \text{ lbs. per sq. in.},$$

we get

$$M = 263{,}400 \text{ in.-lbs.},$$
$$H = 2840 \text{ lbs.},$$
$$M - Hh = 247{,}800 \text{ in.-lbs.},$$

and for the same with lower ends of posts hinged,

$$H = 707 \text{ lbs.},$$
$$-Hh = 127{,}260 \text{ in.-lbs.},$$

showing that the moment in the post due to temperature change is very much augmented by rigid connections, while against horizontal forces the reverse would be true — a fact perhaps so well known as to hardly require any further comment.

Longitudinally, the temperature stresses produced in the posts also differ considerably according to the modes of connection made between the girder and the posts and the number of spans so connected.

Suppose that in Fig. 2, two continuous spans are fixed longitudinally at C and movable at A and the posts firmly fixed at D and rigidly riveted to the girder.

Then a rise t in temperature will tend to displace the point B with respect to D by $t\theta l$, so that H would be acting, as it were, through that distance in the direction as shown in the figure.

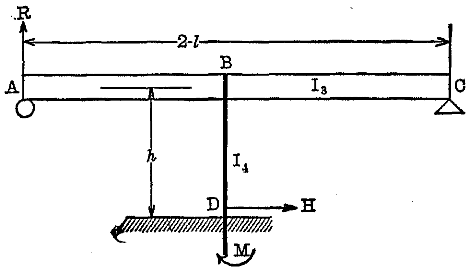

Fig. 2

Calling moments producing compression on the upper fibre of the girder and on the left side one of the post positive, we have for moment at any point of

AB	Rx	with origin of x at A,
BD	$M - Hx$	" " " x at D,
BC	$\dfrac{Rl + M - Hh}{l}x$	" " " x at C.

Again neglecting the effect of direct stresses, we get for the internal work in the frame,

$$\omega = \frac{1}{2\,EI_3}\left\{\int_0^l (Rx)^2\,dx + \int_0^l\left(\frac{Rl + M - Hh}{l}\,x\right)^2 dx\right\}$$
$$+ \frac{1}{2\,EI_4}\int_0^h (M - Hx)^2\,dx,$$

in which I_3 and I_4 represent the moments of inertia of the girder and posts respectively, both considered as being constant throughout.

Then since according to the principles of work

$$\frac{d\omega}{dH} = t\theta l, \quad \frac{d\omega}{dM} = 0, \quad \frac{d\omega}{dR} = 0,$$

we get

$$\frac{2\,l}{I_3}(Hh - M - Rl) + \frac{h}{I_4}(2\,Hh - 3\,M) = \frac{6\,Et\theta l}{h},$$

$$\frac{2\,l}{I_3}(H - Mh - Rl) + \frac{3\,h}{I_4}(Hh - 2\,M) = 0,$$

$$Hh - M - 2\,Rl = 0,$$

from which

$$M = \left(\frac{lI_4 + 3\,hI_3}{2\,lI_4 + 3\,hI_3}\right)\frac{6\,EI_4t\theta l}{h^2},$$

$$H = \left(\frac{lI_4 + 6\,hI_3}{2\,lI_4 + 3\,hI_3}\right)\frac{6\,EI_4t\theta l}{h^3}.$$

If the lower ends of the posts were hinged at D, M would disappear, so that we get

$$H = \left(\frac{I_3I_4}{lI_4 + 2\,hI_3}\right)\frac{6\,Et\theta l}{h^2}.$$

Again referring to the previous example and assuming

$I_3 =$ 30,000 in.^{4}	$l = 50$ ft.
$I_4 =$ 1000 in.^{4}	$h = 15$ ft.

we get for the case of fixed posts,

$$M = 1{,}126{,}400 \text{ in.-lbs.},$$
$$H = 12{,}290 \text{ lbs.},$$
$$M - Hh = 1{,}085{,}800 \text{ in.-lbs.}$$

A comparison of such figures will show that in most cases occurring in practice, the max. moment in the post when the latter is firmly connected to the girder and to the foundation may, without material error, be assumed to be twice that produced when either end is hinged.

The combined action of lateral and longitudinal moments is to throw the greatest compression, in the above case, on the outermost corner on the left side of the post base, where it would amount to, for a 12-in. square post with $I = 1000$ in.^{4} in either direction:

$$\frac{263{,}400}{1000} \times 6 + \frac{1{,}126{,}400}{1000} \times 6 = 8340 \text{ lbs. per sq. in.}$$

By applying the foregoing computations to any form of post sections, it will at once be seen that a considerable stress is produced in certain portions of the column, in the kind of bent discussed, under changes of temperature which are not uncommon.

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