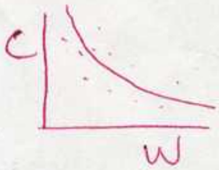
MTM3b Prof. Caldwell 14.2.1989

Measure of Quality. At this secondary level of design, both structural weight and production cost can be important in 'design for economy'. Unfortunately, as will be shown, (see also Fig 1.4) these two objectives usually lead to very different designs. Hence it is important to try to identify the appropriate objective in each design case.

UNIDIRECTIONALLY-STIFFENED PANEL UNDER UNIFORM LATERAL PRESSURE



To explore and illustrate some general aspects of design for economy, consider the typical problem, shown in Fig 2.1 below where a design is required for a flat, singly-stiffened panel L x B. The initial cost of the panel will include both material cost and labour cost, and since the material cost can be directly related to the weight of material, it is possible to include weight minimisation and cost minimisation within the following simple analysis.

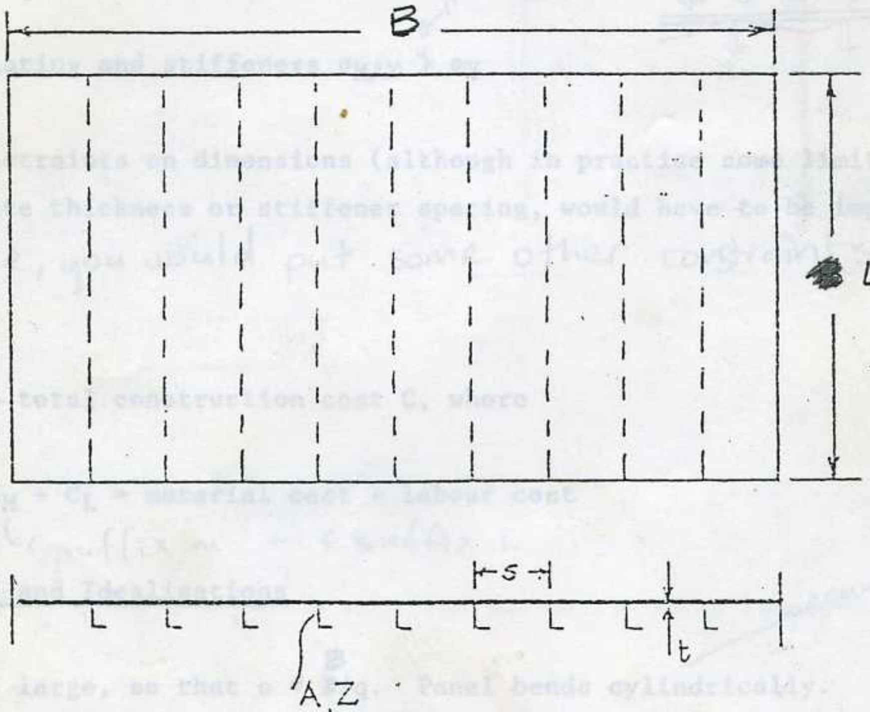


FIG.2.1.

This problem can be formulated as an exercise in design from first principles.

This is a typical shipbuilding design.

Bu tipik bir gemi insaatı dizayn problemi olup, temel mukavemet ilkelerinden yola çıkılarak formüle edilebilir.

Functional Requirements

Panel to withstand a given uniform lateral pressure p over specified area L x B without material yielding. Panel edges may be assumed 'pinned' (simply supported). (not an essential assumption) just to keep the analysis simple.

Design Variables

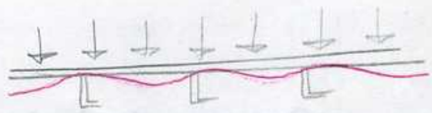
Stiffener spacing s (or number of stiffeners q)

Plate thickness t

Stiffener size and form, expressed by sectional area A and elastic section modulus (with plating) Z.

Constraints

must not be



For both plating and stiffeners $\sigma_{MAX} \not> \sigma_Y$.

No side constraints on dimensions (although in practice some limits, eg. on minimum plate thickness or stiffener spacing, would have to be imposed).

in practice, you would put some other constraints e.g max depth min thickness min s. spacing

Objective

To minimise total construction cost C, where

$$C_T = C_M + C_L = \text{material cost} + \text{labour cost}$$

Csuffix M + Csuffix L

Assumptions and Idealisations

because there's no girder

(a) B/s is large, so that $s \simeq B/q$. Panel bends cylindrically.

(b) Relation between cross sectional area of stiffener A and section modulus Z of one stiffener plus associated effective plating, for any proposed 'family' of stiffeners is (see fig 1.5).

$A = \alpha Z^m$ $\quad\alpha, m$ constants depending on family

(c) All free dimensions continuously variable (not strictly true in practice) thickness 6.0, 6.5, 7.0, 7.5 etc.

(d) Cost relationships

weight of plating
weight of stiffeners

$$C_M = C_{MP} + C_{MS} = \text{plate material} + \text{stiffener material cost}$$
$$= K_1\ (W_P + W_s)$$

in reality this must be $(K_{1P} W_P + K_{1S} W_S)$

where K_1 = material cost per unit weight

W_p, W_s = total weight of plating, stiffeners

Also, assume

$$C_L = K_2 J$$

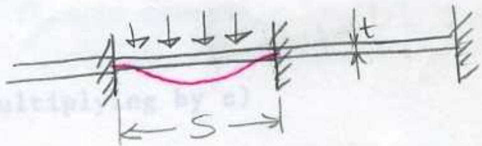
where

J = total length of stiffener-to-plate joints — related to welding

K_2 = cost per unit length of joint.

Analysis

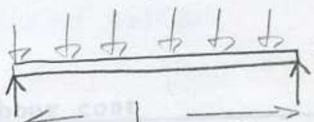
Using simple beam theory for a plate strip s x t x 1, (ends encastré):-



Plating design: $\sigma_{MAX} = \frac{1}{2} p \left(\frac{s}{t}\right)^2 = \sigma_Y$

$$\therefore t = s \frac{p}{\sqrt{2\sigma_Y}} = s\sqrt{\frac{p}{2\sigma_y}}$$

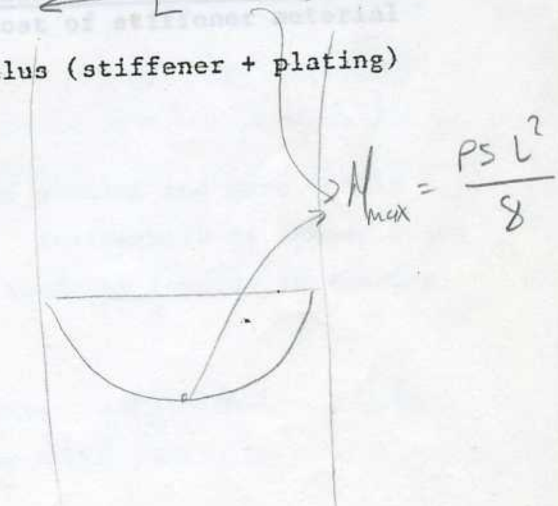
running load ps



Stiffener design $\sigma_{MAX} = \frac{M_{MAX}}{Z} = \frac{psL^2}{8Z} = \sigma_Y$

$$\therefore Z = \frac{psL^2}{8\sigma_Y} = \text{required section modulus (stiffener + plating)}$$

$$\therefore A = \alpha Z^m = \alpha \left(\frac{pL^2}{8\sigma_Y}\right)^m s^m$$



weight of plating

weight of stiffeners

Cost Minimisation

$$C_T = K_1\,[\omega LBt + \omega LAq] + K_2 Lq \qquad \omega = \text{specific weight of material}$$

Hence using $q = B/s$, and the above design equations,

$$C_T = K_1\left[\omega LBs\sqrt{\frac{p}{2\sigma_Y}} + \frac{\omega LB\alpha}{s}\left(\frac{pL^2}{8\sigma_Y}\right)^m s^m\right] + \frac{K_2 LB}{s}$$

Thus stiffener spacing s is the only design variable in this objective function. The problem can be formulated as one of unconstrained minimisation, so that the 'best' design is when $\frac{dC_T}{ds} = 0$

Now we can write

$$C_T = c_1 s + c_2 s^{m-1} + c_3 s^{-1}$$ where C_1, C_2, C_3, depend only on given values.

Hence optimal design is when

$$c_1 + (m-1)c_2 s^{m-2} = c_3 s^{-2}$$

or

$$c_1 s = (1-m)c_2 s^{m-1} + c_3 s^{-1} \qquad \text{(multiplying by s)}$$

ie. when $$\frac{c_1 s}{c_2 s^{m-1}} = (1-m) + \frac{c_3 s^{-1}}{c_2 s^{m-1}}$$

or $$\frac{\text{cost of plate material}}{\text{cost of stiffener material}} = (1-m) + \frac{\text{labour cost}}{\text{cost of stiffener material}}$$

But $\dfrac{\text{labour cost}}{\text{cost of stiffener material}} = \dfrac{K_2 LBs}{sK_1 \omega LBA} = \dfrac{K_2}{K_1 \omega A}$

$= \dfrac{\text{cost per unit length of joint}}{\text{cost per unit length of stiffener}}$

Also, the material costs are proportional to the weights, and for ship stiffeners typically m = 2/3, hence we arrive at the final result that, for least cost design

$$\frac{\text{Weight of plating}}{\text{Weight of stiffening}} = \frac{1}{3} + \frac{\text{Cost per unit length of joint}}{\text{Cost per unit length of stiffener}}$$

Given the overall dimensions, pressures, unit costs, etc, detailed scantlings of the optimal design can easily be found from the above analysis, which is of course only approximate.

For the present we only wish to draw general conclusions about panel design. The first is that if labour costs are neglected, the result is a design for minimum material cost, and hence for minimum weight. In this case the optimal (least weight) design would require the plating weight to be only about one third of the stiffener weight. This is generally impractical and of theoretical interest only. $\frac{W_p}{W_s} = 1.5$ (for most merchant ships)

If labour costs are now included, the resulting design clearly becomes very sensitive to the relative values of welding costs and stiffener material costs. For example, if weld costs were £2 per metre, and the stiffener material cost also £2 per metre then in the least cost design.

$$\frac{\text{Weight of plating}}{\text{Weight of stiffening}} = \frac{1}{3} + 1 = 1.33$$ → this is much more like the practical value (1.5)

which would require a design having much thicker plating and more widely spaced stiffeners than the least weight design. Furthermore if labour costs increase in proportion to material costs, this tendency towards increasing

this tells us very thin plate and many stiffeners

However, where labour cost is high (or low) this might change

e.g: welding cost is £2/meter in the UK

the proportion of plating weight in the structure should also be increased. Perhaps the main result of this elementary exercise is to show that, in design for production, simple ratios of labour to material costs are emerging as very important and useful parameters which can be used analytically to guide the structural designer.

FLAT STIFFENED PANELS - FURTHER RESULTS

Many more elaborate and rigorous studies of flat panel design have been made using formal optimisation procedures incorporating more constraints on behaviour and dimensions. The results of some work reported in ref. 4 are summarised in Table 1. A mild steel deep tank bulkhead 8m wide x 5m deep is required to withstand a hydrostatic head of 8m above its base. Unit costs of material and of production are specified. The stiffening may be uni-directional (vertical) or may include a horizontal girder at mid-depth to form a grillage. There are 8 design variables:-

Spacing of vertical stiffeners (beams)
Web depth, thickness and flange area of girder
Plating thickness

Constraints are imposed on:-

Bending and shear stress in stiffeners and girder
Bending stress in plating
Depth/thickness ratios of webs of beams and girder (to prevent local buckling)
Flange areas of beams and girder.

Table 1 shows 6 'optimised' designs. Designs 1-4 are for vertical stiffening only; designs 5 and 6 include a cross-girder. Note the contrast between design 1 (for minimum weight) and design 2 (minimum cost), likewise designs 5 and 6. Fig 2.2. clearly shows the very different results for designs 1 and 2. Design 3 is for a mixed objective function (see first lecture) incorporating both weight and cost.

Such optimisation studies generally assume that design variables (g. plate thickness) are continuously variable. In practice not only are plates and

Results of deep tank bulkhead design example

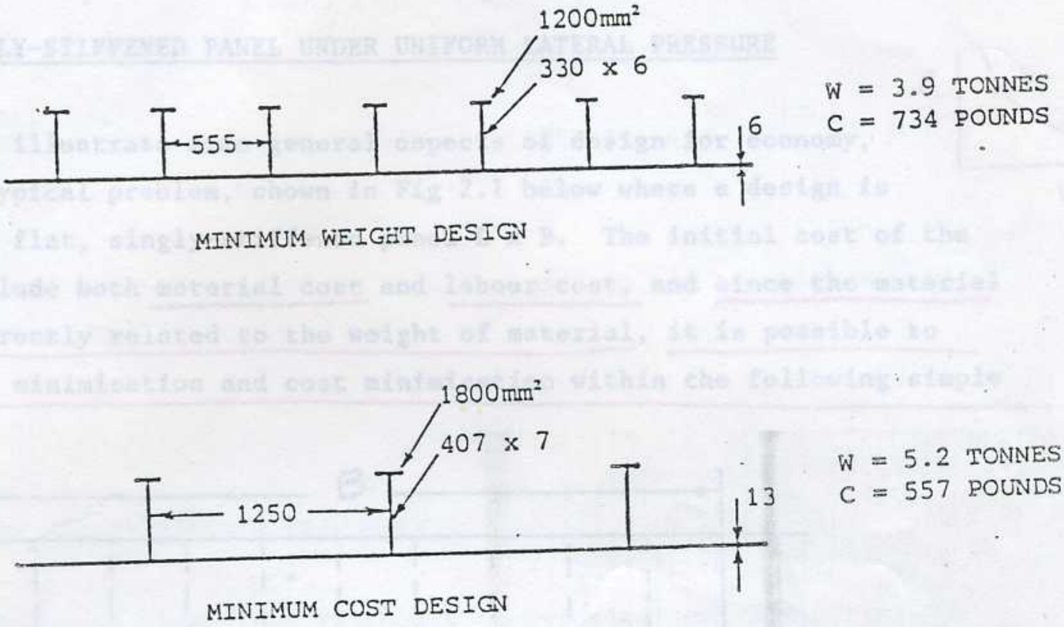
Design option	Number of stiffeners	Plating thickness, mm	Beam: Web depth, mm	Beam: Web thickness, mm	Beam: Flange area, mm^2	Girder: Web depth, mm	Girder: Web thickness, mm	Girder: Flange area, mm^2	Total cost, £	Total mass, tonnes
1 Panel design										
minimum weight	17	6	330	6	1200	-	-	-	734	3.91
2 Panel design										
minimum cost	7	13	407	7	1800	-	-	-	557	5.23
3 Panel design										
minimum composite objective function, with $k = 0.3$	10	10	379	7	1600	-	-	-	599	4.69
4 Panel design										
minimum cost with standard elements	8	12	400	8	1800	-	-	-	583	5.23
5 Grillage design										
minimum weight	15	6	244	5	600	1049*	17*	-	756	3.71
6 Grillage design										
minimum cost	7	12	339	6	1300	839	14	1800	636	4.93

$u = k\frac{W}{W_0} + (1-k)\frac{C}{C_0}$

* Some adjustment to the design of this girder would be necessary to ensure stability against tripping.

TABLE 1

more like warship design



more like merchant ship design

objective function is very important and determines the results.

FIG. 2.2.