Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 37 (1982)

Artikel: Fatigue considerations in the design of concrete offshore structures

Autor: Price, W.I.J. / Tricklebank, A.H. / Hambly, E.C.

DOI: https://doi.org/10.5169/seals-28946

Fatigue Considerations in the Design of Concrete Offshore Structures

Fatigue et conception des structures offshore en béton

Ermüdungsfestigkeit und Konstruktion von Offshore-Betonbauten

W.I.J. PRICE
Partner
Gifford and Partners
Southampton, UK

A.H. TRICKLEBANK
Associate
Gifford and Partners
Southampton, UK

E.C. HAMBLY
Consulting Engineer
Berkhamsted, UK

SUMMARY
Fatigue analyses were carried out on three types of oil production platforms and a pontoon type hull using a North Sea wave climate. Two types of floating wave energy converters were analysed using a North Atlantic wave climate. Fatigue criteria were only important for oil production platforms at stress concentrations and on components sensitive to smaller waves. However, they have a strong influence on the design of main members of wave energy converters and make a reinforced concrete hull uneconomic.

RESUME
Des analyses de fatigue ont été effectuées sur trois types de plateformes pétrolières et sur une coque de bateau-ponton sollicités par un régime de vagues type Mer du Nord. Deux types de convertisseurs d'énergie flottants ont été sollicités par un régime de vagues type Atlantique Nord. Les critères de fatigue pour les plateformes pétrolières ne se sont révélés importants que pour les concentrations de contrainte et pour les éléments sensibles aux petites vagues. Cependant, ils ont une forte influence sur la conception des éléments principaux des convertisseurs d'énergie des vagues et ils rendent une coque en béton armé non économique.

ZUSAMMENFASSUNG
Es wurden verschiedene Ermüdungsuntersuchungen durchgeführt, nämlich an drei Erdölplattformen und einem pontonartigen Schiffsrumpf, wobei ein Nordseewellenklima verwendet wurde. Für zwei verschiedene schwimmende Wellenenergiewandler wurde ein Nordatlantikwellenklima angenommen. Bei den Erdölplattformen spielten die Ermüdungskriterien nur an Spannungskonzentrationen sowie an gegen kleinere Wellen empfindlichen Bauteilen eine Rolle. Bei der Konstruktion der tragenden Bauteile von Wellenenergiewandlern gewinnen sie jedoch stark an Bedeutung und machen einen Eisenbetonrumpf unwirtschaftlich.

1. INTODUCTION

The design study described in this paper was undertaken as a part of the Concrete in the Oceans programme funded by the Department of Energy and the UK Offshore Industry, to determine how serious a problem fatigue is in the design of offshore structures. It is published by permission of the Management Committee. The structures analysed are shown in FIGS 1 and 2. They are:

- Prestressed and Reinforced Concrete Tower Platforms
- Prestressed Concrete Articulated Column Platform
- Prestressed Concrete Pontoon Hull for Petrochemical Plant
- Wave Energy Converter (WEC) with a Reinforced Concrete Raft Hull
- Wave Energy Converter (WEC) with a Prestressed and Reinforced Concrete Spine Hull

This paper outlines the methods used and the assumptions made, and summarises the main conclusions. A fuller version of it is contained in reference [1].

2. LOADING

In the fatigue calculations only wave loading has been considered as fluctuating because it created the most arduous conditions. However, in more rigorous analyses it may be necessary to consider additionally several combinations of fluctuating loads from currents, wind, hydrostatic pressures, temperature effects, machinery, plant and moorings.

The stresses for various levels of loading were calculated deterministically for the oil platforms and pontoon hull, using eight blocks of waves which describe the wave climate in the North Sea. Their range and occurrences for a 100 year period are plotted in FIG 4(i). Damaging stresses in a structural detail may only be caused by waves from a limited number of directions, so the simplifying assumption has been made that only 50% of the waves pass in the particular directions most critical to the detail under consideration.

For the raft form of the wave energy converter, FIG 2(a), the loading is obtained from the wave height/exceedance data for the North Atlantic near the island of South Uist off the west coast of Scotland [2]. The number of occurrences, n, in a period of 25 years derived for each block with a mean wave height, H, is given by: $\text{Log } n = 8.5\ (1-H/23.5)$ - (1)

The shorter return period of 25 years reflects the shorter nominal life of wave energy structures compared with petrochemical structures. No reduction for directionality is taken, as the directional spread for the larger waves is likely to be confined mainly to the forward quarter directions because of the location. Greater directional spread may be expected from smaller waves but the panel loadings which they produce are not strongly dependent on heading to the waves.

In the case of the wave energy converter with the spine hull, FIG 2(b), a spectral analysis was undertaken based on the response in bending of a hydrodynamic model to random fully developed seas, with a Pierson-Moskowitz spectrum and suitable spreading function, in a three dimensional wave tank.

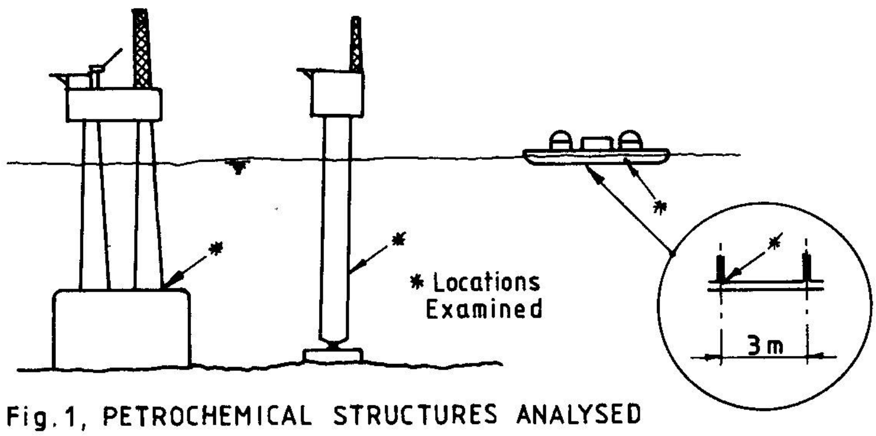
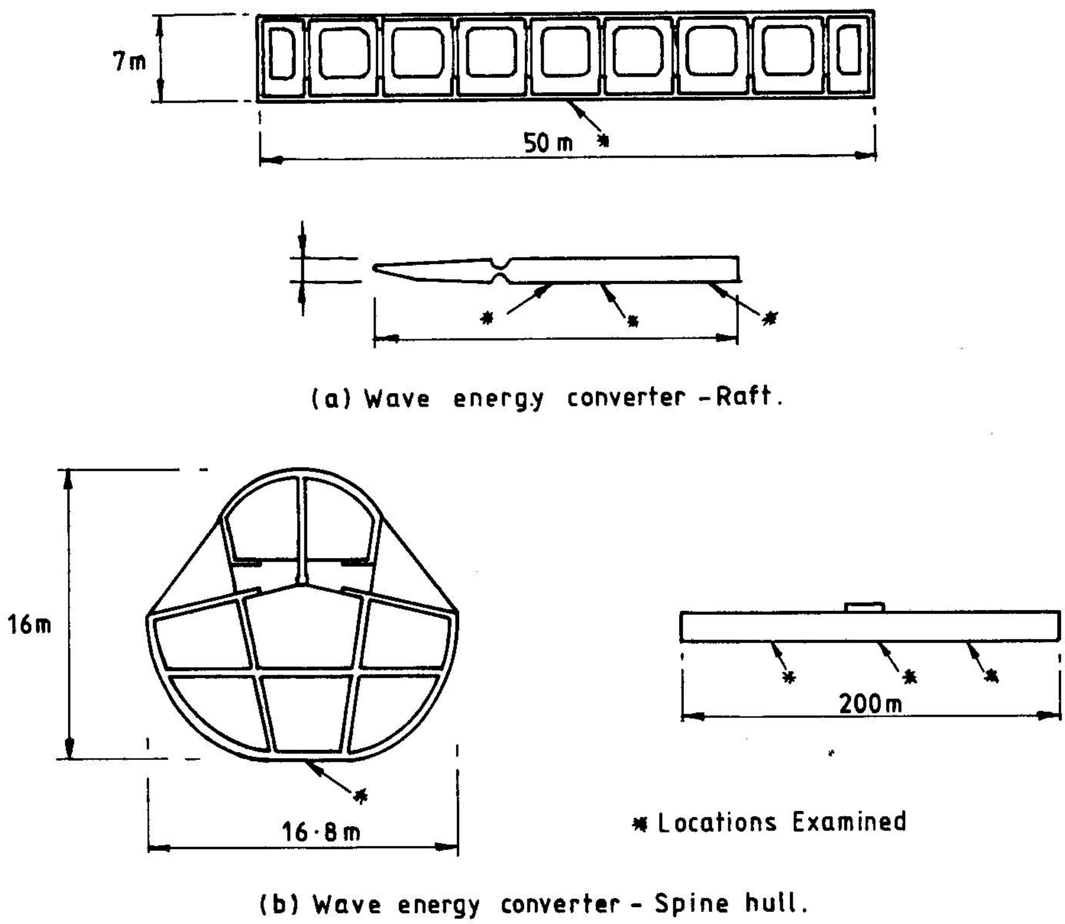


Fig.1, PETROCHEMICAL STRUCTURES ANALYSED



(b) Wave energy converter - Spine hull.

Fig. 2 WAVE ENERGY STRUCTURES ANALYSED

From this analysis a bending moment exceedance curve was produced and this was used to determine the most probable number of stress occurrences in any given period of time.

3. FATIGUE CHARACTERISTICS OF MATERIALS

3.1 Concrete

If the fatigue strength of normal portland cement concrete is expressed as a fraction of the static strength, So,it can sustain repeatedly for a given number of cycles, then this strength is essentially the same whether the stress regime is tension,compression or flexure. The S-LogN or Wohler curve of normal portland cement concrete in tension, compression and bending, is approximately linear, as also is the Goodman diagram, so that they can be represented by a single diagram for which the equation is:

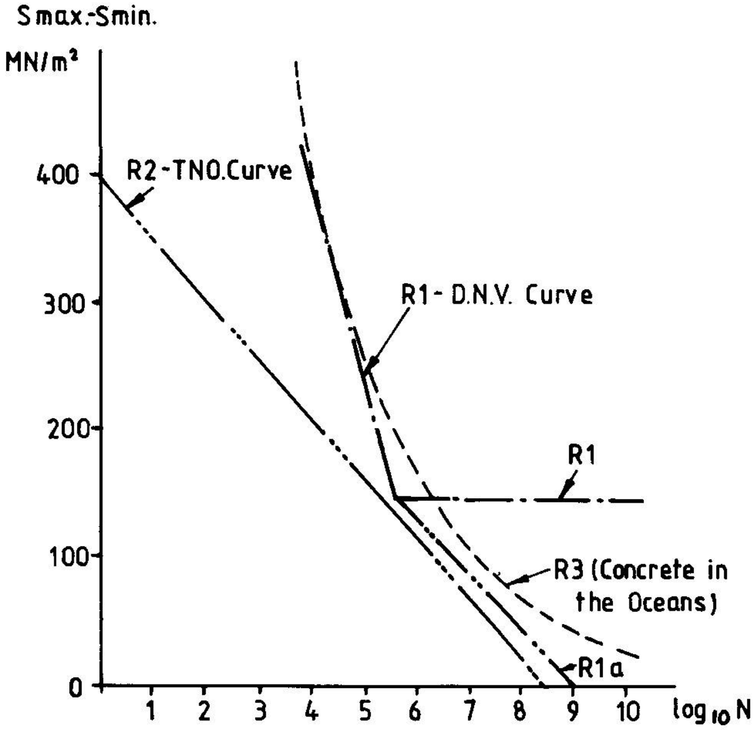


FIG.3 S-N CURVES FOR STEEL REINFORCEMENT

Log N = C(1 - (Smax-Smin)/(So-Smin)) - (2)
Where Smax and Smin = Maximum and minimum of stress range, Sr,
So = factored static strength
= αfk/γm
α = stress gradient factor (unity for uniform stress)
fk = characteristic strength
γm = partial safety factor for materials

The calculations were carried out for two forms of this relationship. One based on TNO procedures [3], with C = 12.6 and an endurance limit at N = 2 x 10^6 of (Smax-Smin)/(So-Smin) = 0.5 [Curve C1 in FIG 4 (iv)]. The other is based on DNV rules [4], with C = 10 and no endurance limit [Curve C2 in FIG 4 (iv)]. Curves V1 and V2 used for shear calculations are similar to C1 and C2 with shear force replacing tensile or compressive forces.

3.2 Reinforcing Steel

The S-LogN curves given in design codes take the forms of R1 (DNV ref [4]) and R2 (TNO ref [3]) (FIG 3). The equation for R1 is:
Log N = 6.5 - (2.3(Smax-Smin)/So)-0.002 Smin - (3)
where So = fsy/γm
fsy = yield strength of steel
It has an endurance limit of (Smax-Smin) = (165/γm) - 0.33 Smin.
The equation for R2 is:
Log N = 8.4 (1-(Smax-Smin)/400) - (4)

Recent experimental work on the fatigue of reinforcement in concrete beams subject to bending and immersion in sea water, carried out as part of the Concrete in the Oceans programme, demonstrated the influence of crack blocking and corrosion [5]. The results fit a linear LogN-LogS relationship of the form:

$$\text{Log } N = 17.464 - 4.83 \text{ Log } Sr \quad - (5)$$

where Sr is the initial stress range. The 97.5% survival limit is given by:

$$\text{Log } N = 17.088 - 4.83 \text{ Log } Sr \quad - (6)$$

Curve R1a is a suggested compromise for a design curve whose upper portion is the same as R1 (DNV rules) and whose lower portion lies between R2 (TNO procedures) and R3, without a fatigue limit. The equation of the lower portion is:

$$\text{Log } N = 9 - 0.0237\,(Smax - Smin) \quad - (7)$$

3.3 Prestressing Steel

Only fully bonded prestressed designs have been considered in this analysis with the concrete section remaining uncracked, except for a single occurrence of extreme loads. Taking a modular ratio in the range of 4.5 to 7, the stress ranges in the tendons usually fall below the values regarded as significant for fatigue according to present rules [4][6]. The question may be raised whether complete bonding is achieved in practice under difficult grouting conditions and whether the assumption of full bonding is appropriate in all circumstances.

4. CUMULATIVE FATIGUE DAMAGE

The cumulative damage that is suffered as a result of all the stress blocks, "a" to "h" in FIG 4 is calculated using Miner's Sum:

$$\sum_{i=a}^{i=h} ni/Ni \leqslant K \quad - (8)$$

To avoid fatigue problems the value of K must not be exceeded. For steel members K is usually taken as 1. Tests on plain concrete have shown that Miner's sum gives a scatter of values with a log-normal distribution with a mean value generally less than 1 [7]. Waagard suggests that values between 0.2 and 0.5 are appropriate [8] and DNV rules take the lower value [4].

5. FATIGUE LIMIT STATES

The Miner's sums were calculated for actual designs of several types of structures shown in FIGS 1 and 2. Some of the analyses and results are illustrated in diagrammatic form in FIG 4 for specific conditions and locations. In the deterministic calculations (FIG 4), wave heights in diagram (i) have been translated into stresses in the more vulnerable locations in diagram (ii). These stresses have been combined with frequency, n, in diagram (iii) and related to S-logN curves in diagram (iv). The values of n/N for each wave height range are plotted in diagram (v) and summed for each appropriate fatigue damage curve. In FIG 4, large values of the Miner's Sum were obtained, but without the "hot spot" and its stress concentration effect, the fatigue damage was generally small (see Table 2).

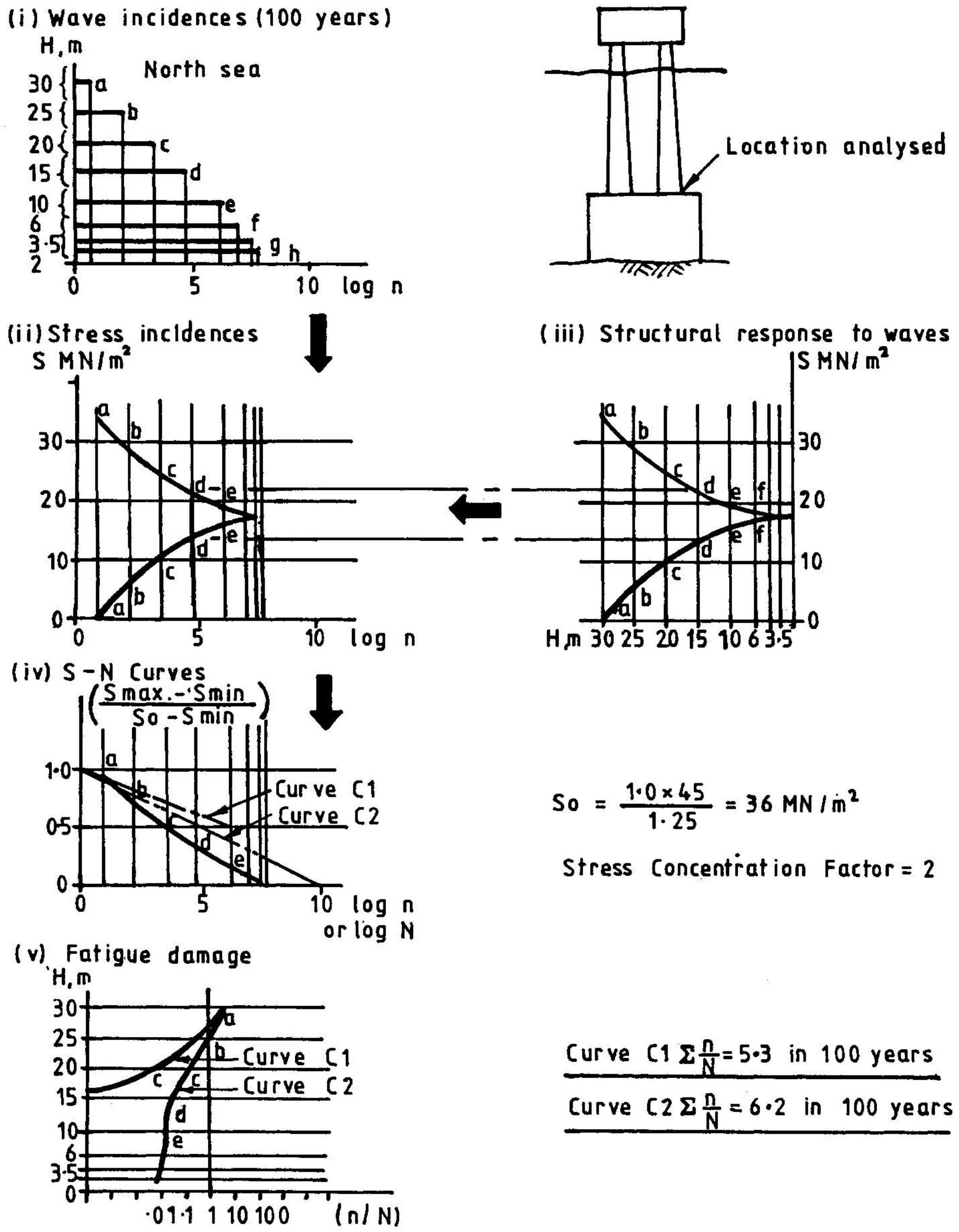


Fig.4 P.S.C. TOWER PLATFORM : HOT SPOT IN CONCRETE AT BASE OF TOWER.

For the case illustrated in FIG 4, a simultaneous disadvantageous change of 20% to the number of waves, the mean stress level, the stress range, the characteristic strength and the S-N curve changed the value of Miner's Sum by five orders of magnitude.

In the spectral analysis of the spine hull the input of load effect is in the form of bending moment or shear force occurrences. This has been translated into effective stress ranges for various values of the partial load factor, γf. Calculated fatigue damage was plotted logarithmically against γf, to show that a load factor in excess of 2.04 would be required to satisfy the criterion of $n/N \not> 0.2$.

6. CONCLUSIONS

The main results of all the analyses are summarised in Table 2. In general terms, fatigue strengths of the oil platforms and pontoon hull were adequate, except perhaps at stress concentrations and in components that may be as sensitive to the action of small waves as to the action of large waves.

Floating wave energy structures are more vulnerable to fatigue. Prestressed hulls suffered little fatigue damage under overall bending, but areas which are difficult to prestress, such as corners, where the strength may be provided by conventional reinforcement, may be critical. Hulls made of reinforced concrete will require a substantial increase in the proportion of reinforcement to avoid premature fatigue damage and the need for welding and lapping of bars for economical construction will exacerbate the fatigue problem and make such structures impracticable.

7. REFERENCES

1. Price W I J, Hambly E C and A H Tricklebank: Review of Fatigue in Marine Structures. CIRIA/UEG, Concrete in the Oceans; P5/Final Report, London 1981.
2. Tann H M: The Estimation of Wave Parameters for the Design of Offshore Structures. Institute of Oceonographical Sciences, Report No 23, Taunton 1976.
3. Monnier T: Fatigue Strength Procedure for Concrete Offshore Structures. TNO Report Delft October 1975.
4. Det Norske Veritas: Rules for the Design, Construction and Inspection of Offshore Structures, Appendix D Oslo 1977.
5. Paterson W S, Dill M J and R Newby: Fatigue Strength of Reinforced Concrete in Sea Water, CIRIA/UEG, Concrete in the Oceans, P6/Final Report, London, April 1981.
6. Hawkins N M: Fatigue Considerations for Concrete Ships and Offshore Structures. Proceedings of Conference on Concrete Ships and Floating Structures, University of California 1975.
7. Leeuwen J Van and A J M Siemens: Miner's Rule with respect to Plain Concrete. Boss 79, 2nd International Conference on Behaviour of Offshore Structures, London 1979.
8. Waagard K: Fatigue Strength Evaluation of Offshore Structures. Proceedings of American Concrete Institute Convention, Dallas, February 1981.

TABLE 2 SUMMARY OF FATIGUE DAMAGE CALCULATIONS

Structure	Material	Location	Stress Conc. Factor	Fatigue Damage n/N: Period Years	Concrete: fk MN/m^2	Concrete: C1	Concrete: C2	Reinforcement: R1	Reinforcement: R1a	Reinforcement: R2	Reinforcement: R3	Tendon Sr MN/m^2
Tower Platform	Prestressed Concrete	Base of Tower	1.0	100	45	0.00	0.01					125
		Base of Tower	2.0	100	45	5.3	6.2					
	Reinforced Concrete	Base of Tower (Tower flooded)	1.0	100	45	0.00	0.01					
		Base of Tower	1.0	100				0.00		0.56	0.00	
Column Platform Articulated	Prestressed Concrete	Mid-height	1.0	100	45	0.00	2.7					
Pontoon Hull	Prestressed Concrete	Base-Longitudinal Compression	1.0	100	40	0.00	6.0					
		Base-Transverse Bending	1.0	100	40	0.00	0.03	0.00		3.2	0.16	
		Side Wall-Shear	1.0	100	40	V1 0.00	V2 15.0					
Wave Energy Converter - Raft Hull	Reinforced Concrete	Side Wall	1.0	25	60	0.06	0.10					
		Side Wall - Fore/Aft	1.0	25				0.40	3.4			
		Side Wall-Midship	1.0	25				3.6	9.6			
		Side Wall-Shear	0.6	25		V1 0.00	V2 0.20					
Wave Energy Converter - Spine Hull	Prestressed Concrete	Midship-Bending	1.0	25	80	0.00	0.02					76
		¼Point-Shear	0.6	25		V1 0.00	V2 0.20					
	Reinforced Concrete	Midship-Bending	1.0	25				0.41	1.58			
		¼Point-Shear	1.0	25		V1 0.00	V2 0.20					