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Nonlinear Analysis Comparison to Predict Design Charts for Normal and Lightweight Prestressed Concrete Double Tee Beams

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Abstract— Precast prestressed concrete double tee is an economic bearing element which can be prepared into a large span to coverage large area. Self-weight of the beam and overlay slabs or finishing layers considered a major part of the load carried by prestressed concrete beams. If all or part of the beam can be manufactured using lightweight concrete, there is a prospective for economic savings because its self-weight could be reduced up to 20%. This research paper represent a comparison between double tee beam made from lightweight concrete vs. normal weight in the basic of designing issues for its major aspects. The study based on the section adopted by the Precast/Prestressed Concrete Institute, and a parametric analysis carried out to predict a design guide for both lightweight and normal weight section. Load-span charts obtained and recommended to used with clear way to show the effect of reducing the total weight of the section by using lightweight concrete. Then the effect extend to include the camber at erection and long-time camber. In general the variation of load bearing capacity of the section raised much more for lightweight with respect to normal weight concrete. Also, better response in its camber behavior shown at both stages (at erection up to long-time).
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Keywords— Precast, Prestressed concrete, Double tee beam, Lightweight Concrete.

1. Introduction

Since in the late nineteenth century, mostly in many state in USA, lightweight aggregate concrete has been adopted as construction material, that could be an alternative for the normal dense aggregate. For economic considerations, it has been adopted in structural concrete for many years purely covering many cases. For sure, the most apparent characteristics of lightweight aggregate concrete is its final gated density which is always significantly less than normal concrete. It has been founded that concrete made with such lightweight aggregate can be as much as one-third lower density than that of normal concrete made with sand and gravel or crushed rock aggregates. [1],[2]

Lightweight concrete classified by the British Standard, BS 8110:Part2 : 1985 as concrete having density less than 2000 kg/m^3. While RILEM's functional classification define light structure when its concrete having oven dry-density less than 2000 kg/m^{3}with compressive strength more than 15 N/mm^2 . [3],[4]

Based on that, double tee beams chosen in this research paper is within that definition, to be tested numerically by finite element method to present a comparison that show the effect of replacing normal weight by lightweight concrete overall double tee beams. The main objective of this research works is to carry a comparison for lightweight vs. normal weight concrete double tee beam and study its effect on the mean characteristic behavior of the beam represented by load-span charts

2. Overview on Research Subject

The commercial request for light, strong concrete has increased in recent years because of its at first consider economies and has the advantages over usual concrete in a variety of its applications on constructions. Various lightweight concrete structures, laying on wide range started by low-rise houses to multistory buildings, bridges to marine and offshore structures that apparently founded in many parts of around the world. ACI Committee 514 has specified a comprehensive outline of the most applications of lightweight concrete and its future application potentials. Unfortunately, within the Middle East region where we belong is up (specially in Iraq) till now have no experience on large-scale structural applications of lightweight concrete. Because there is an overall lack of understanding on the production technique for this type of material, which needshigher skills and technology back up with respect to ordinary normal weight concrete works. Also, the available information locally on the its performance of this material is inadequate to provide sufficient guidance and assurance to the designers.

In general, most of the lightweight concrete members follow the rules given by the main codes of practices (ACI 318, BS 8110), where these rules are mostly based either on researches carried out within 1960s, subsequent to which material technology has advanced considerably, or on works that stay behind and mostly unpublished or unreachable to others. Several obtained researches in recently like **Swamy and Lambert**, 1984 [5]; **Ahmad and Barker**, 1991 [6]; and **Ahmad and Batts**, 1991 [7] works in this field in limited range. For that and more, it is essential need to critically check the existing code provisions in the perspective of the advances in material technology within the last two decades in a backdrop to build designer’s confidence. This goal aimed to be achieved by directing this research paper to get this gain.

3. Finite Element Idealization

- Concrete has been modeled by using the 20-noded isoparaimetric brick element
- Prestressing and reinforcing bars were simulated as an axial members embedded within the concrete elements.
- Behavior of concretein compression was simulated by elastic-plastic work hardening model followed by a perfectly plastic response, which is terminated at the onset of crushing [8].
- Behavior of concrete in tension was modeled by using a smeared crack model with fixed orthogonal cracks with the inclusion of models for the retained post-cracking stress and reduced shear modulus.
- Nonlinear equations of equilibrium have been solved by an incremental-iterative technique operating under load control.
- Standard and modified Newton-Raphson methods were considered as solution algorithms.

Finite element formulation and full idealization with alldetails of the constitutive models that has been adopted and followed in this paper were founded in reference [9]. Also, the adopted computer program **3DNFEA** (3-DimensionalNon-linear Finite Element Analysis) was briefly described in the same reference.

4. Tested Double Tee Beam Samples

Based on previous studies carried out by Hussam [10], on a series of double tee beams, (experimentally and numerically), the research works extended to include the effect of lightweight factors and provide the best guide for designing double tee beam multi-choice span length. Double tee beams generally works as units in roofing/flooring parts. The section used was taken from PCI Design Handbook—Precast and Prestressed Concrete that had been published in 2004 under its sixth edition.

5. Geometry and Section Properties of Tested Double Tee Beams

The section properties of all beams used in this research shown in Table below for both normal weight and lightweight beams. The same cross-sectional area used for all beams equal to 0.63m^2, with moment of inertia equal to 35.82×10^{-3} m^4. The used beam was pre-topped beam with total depth of 863.6mm and neutral-axis fall in 654.5mm from the bottom.

Grade 270 strands with diameter of 12.7 mm used in this study were it made to meet the requirement as given in the standard ASTM416, where the main characteristic strength of these strands is 1850 N/mm^2.
The adopted data of lightweight and normal weight concrete properties in term of cube compressive strength, flexural tensile strength, Splitting tensile strength and elastic modulus of elasticity were listed in Table 1 below. The mean cube strength for lightweight concrete is 43 N/mm^2 compared to 47 N/mm^2 of the normal concrete. It is clearly shown that the strength of lightweight concrete is somewhat lower than the strength achieved by the normal weight concrete.

Table 1 Material properties for normal and lightweight concrete.

	Normal weight Concrete		Lightweight concrete	
	Weight (kg)	Strength	Weight (kg)	Strength
Compressive Cube Strength (N/mm^2) (100×100×100mm)	2.39	47	1.98	43
Flexural Tensile Strength (N/mm^2) (100×100×500mm)	11.8	6.43	10.9	6.09
Splitting Tensile Strength (N/mm^2) (150dia.×300mm)	12.02	3.25	11.1	3.0
Elastic Modulus (kN/mm^2) (150dia.×300mm)	12.2	32	11.0	25

The module of rupture used for lightweight and normal weight concrete are 6 N/mm^2 and 6.6 N/mm^2 respectively. The splitting tensile strengths taken for lightweight and normal weight concrete are 3 N/mm^2 and 3.25 N/mm^2 respectively. obviously shown that the tensile strength of lightweight concrete is a little lower than for normal weight concrete. The elastic module for lightweight and normal weight concrete are 25 kN/mm^2 and 32 kN/mm^2 respectively. The value of the lightweight concrete was about 0.7 times of the normal weight concrete.

All beam tested numerically was follows the dimensioning shown in Fig. 1, where its length taken to be from 12m to 30m span. Mostly in practice, double tee members laid under same function which is either floor or roof, that restricted the type of loading on being in shape of uniform distributed over the full span. Therefore, all loading considered in this research work to be uniformly distributed. Various amount of prestressing number of tendons used as a case number one, and various value of effective prestressing force adopted for case number two.

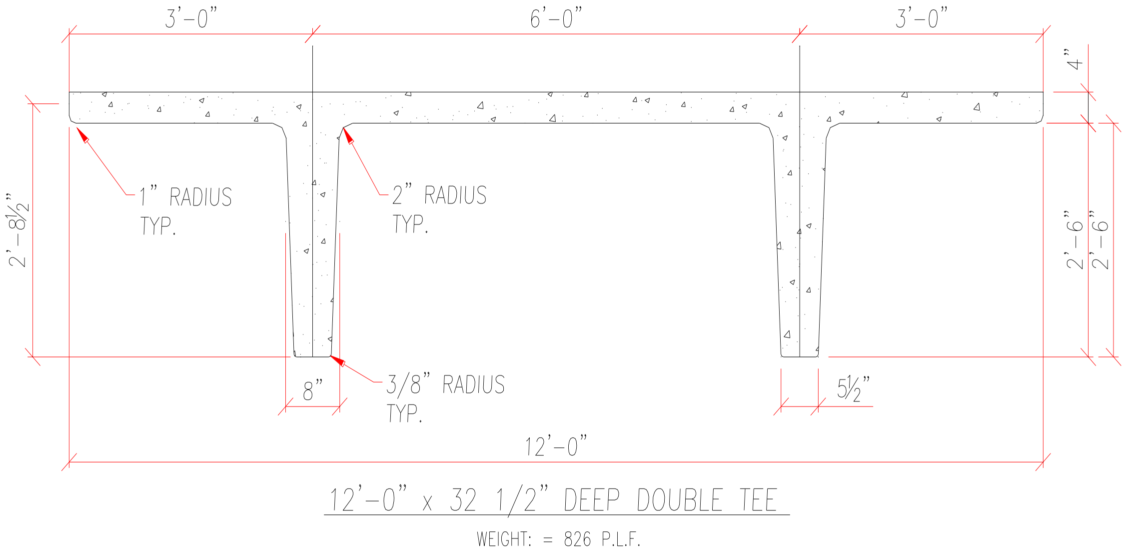

Fig. 1 Double tee section dimension

6. Method of Analysis

- Within the reference Hussam [10], and many other researches done by the same author, good agreement on the overall results between the finite element method of analysis and the experimental test to matching the behavior of double tee beams under general state of loading and specially flexure. Which could be the basic to carry out this research, by considering the finite element technique as a powerful tool to run that much of analysis and create this guide.
- From the general cases of using the double tee beams in construction of offices type of function, the analysis consider an office superimposed live loading ranges around 250kg/m^2 plus a 120kg/m^2 superimposed dead load and more 120kg/m^2 loading came from present a 50mm topping. Which about 490kg/m^2 total superimposed uniform service load and 770kg/m^2 an ultimate load.
- Same technical data used by Hussam [10] to model the required finite element model repeated herein in this research study, including the modeling of shear reinforcement. So, the segment modeled using 20-node isoparametric hexahedral brick elements and its divided into 148 brick elements, making use the benefit of symmetric of section and loading. symmetry gave less number of element need to simulate the section by considering one quarter of the beam
- Hussam [10] represent loading application by using equivalent nodal loads distributed at top face of the overall flange, and it was an active method to be reused herein.
- All analyses with finite element have been carried using the 27-point rule, with 4% convergence tolerance.
- Non-linearity equations were solved by the well known modified Newton-Raphson method, where stiffness matrix is updated at the second iteration of each increment of loading.
- External loading applied in non-uniform increments, where large range of increments applied at the first stage of loading, then get closed near the ultimate state of loading.

7. Resulting Charts for Prestressed Concrete Double Tee Beams

Precast and Prestressed Concrete institute suggest in its handbook a typical sections for double tee beams, that have been adopt on of then to consider in this research paper to present design charts. These charts are organized for provide a useful help for straightforward and fast design of lightweight and normal weight prestressed double tee beams, by carrying out a huge number for computer runs which indeed takes much time.

Computer calculation through software program need accurate input data, to predict an accurate results and consider as aids to preliminary sizing, that requested to be judged by sound of engineering experiences.
The section adopted herein was the same overall the study, but with different prestressing amount and various length to create the design chart for service superimposed load-span guide. Data below shows the designated sample for each beam tested.

128-S = 12 tendons of 8/16 diameter of strands in straight layout
148-S = 14 tendons of 8/16 diameter of strands in straight layout
168-S = 16 tendons of 8/16 diameter of strands in straight layout
188-S = 18 tendons of 8/16 diameter of strands in straight layout
188-D1 = 18 tendons of 8/16 diameter of strands in depressed in one point layout
208-D1 = 20 tendons of 8/16 diameter of strands in depressed in one point layout

Safe loads shown do not include any superimposed dead loads because these elements are pre-topped and are typically used in parking structures. Also, loads shown in design chart below are live load. Furthermore, long-time cambers do not include live load.

The process start from 12m long and carry out full loading analysis for checking its capability and considering the design. After that a recheck by changing the length in steps, with carrying out sub-check for the amount and arrangement of the prestressing value (number and size of tendons). Fig. 2 and Fig. 3 shows the design guide for normal weight and light weigh prestressed double tee beam, represented by it service superimposed load-span variations. The predicted behavior shown in load-span charts were the ability to cover more span by adopting lightweight concrete with respect to normal one. Also, clearly shown that the amount of prestressing could handle the situation by increasing its value to span more distance and take over the weight issue. For short span, the percent of increase range within 8-10%, while for long span the lightweight concrete double tee beam can carry more about 60%. Increasing the amount of straight prestressing tendons could help by increase the ability to carry more load for the same length with about 10-15%. While this percent jumped to reach 25-35% when the prestressing depressed at one point.

All Span-Load charts were developed in accordance with the requirements of the "Building Code Requirements for Reinforced Concrete", ACI 318-02 [11] where all provisions followed and considered for the behavior either in compression or in tension. For additional researches on the investigated of double tee beams experimentally and numerically, check references ([12], [13], [14], and [15]).

As well known that design charts is an open options for the designer to pick their choice from wide range of data. So it is important here to show the effect of beam weight in six cases of beams types. These beams differs on its amount of prestressing and its arrangement, as describe before. Fig.4 and Fig.9 shows the resulted load-span charts for both normal to lightweight DT beams regarding different prestressing arrangement and amount. The using lightweight concrete could help to increate covering span up to 10% with respect to normal weight concrete, and that ration increase itself with increasing the amount of prestressing tendons to reach 14%. Same response shown when changing the arrangement of prestressing from straight to depressed tendon in one point, within that range.

While Fig. 10 to Fig.15) shows the variations for its mid camber at the stage of erection for both normal and lightweight concrete. Herein clearly shown the effect of using lightweight concrete by its higher values regarding to the normal weight. Also, the effect of prestressing amount help more much by giving more camber and could fix the case when long span used. Lightweight concrete double tee beam camber 7% more than normal weight for short span, while this values double to reach 6 times for long span.

Clearly appear the effect of concrete weight on the behavior of beam represented by its camber at erection, where there are almost double values given by lightweight concrete with respect to normal one. The overall response seems to be parallel along the variation of span length. Starting with initial value for camber and increased to its maximum with optimal span length, then decreased to its lower values for long span. That optimal span length range between 16-20m, where almost maximum camber appear.

All charts for straight tendons range increasingly with almost closed range, but that range jumped to higher values when its change to depressed at one point as shown in Figs. (13 and 14) that jumped reach 33% increase in the same amount of prestressing numbers. Like in (188-S and 188-D1). Also, again that jumped repeat when increasing the amount of prestressing from 18 tendons to 20, with almost the same percent.
Also, Fig.16 to Fig.21 shows its variation for long-time camber, where almost within the same response the lightweight beams predict higher values and give better behavior with respect to normal weight concrete. Again, for short span the effect is much less than for long span, where its percent of increasing start by 6% to reach 5 times. Same response shown in long-time behavior but with higher values in the same parallel outline. The optimal range give double maximum long-time camber between lightweight concrete vs. its normal one, for the same span length. Also, depressing of tendons give 25% more long-time camber than the straight one.

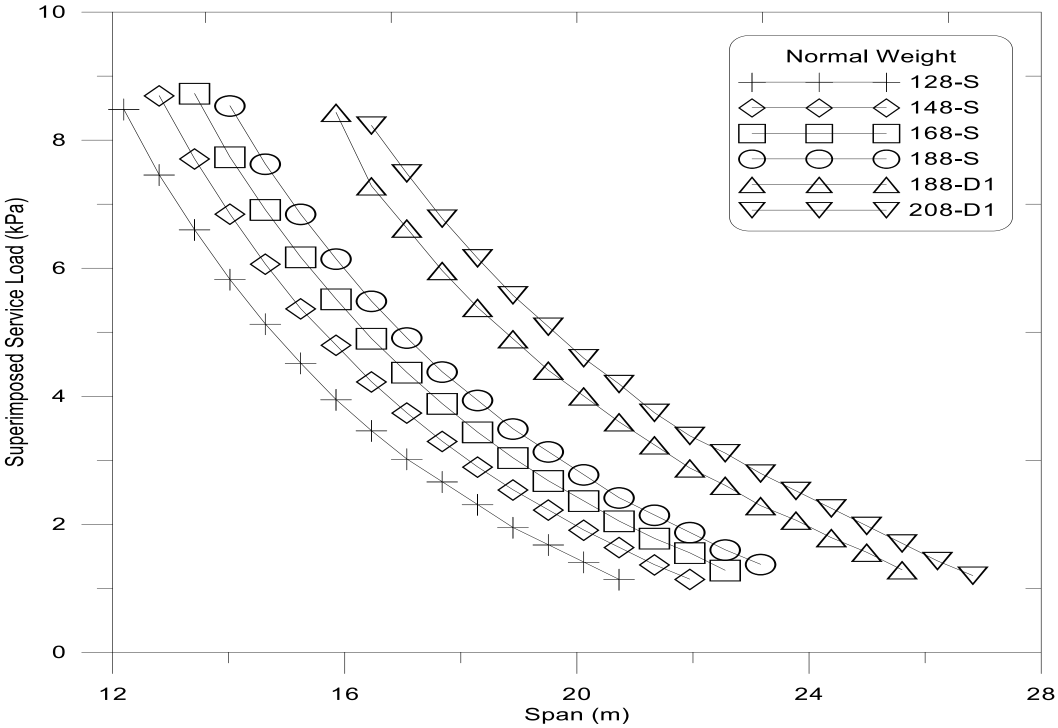

Fig. 2 Load-span charts for normal weight DT beams

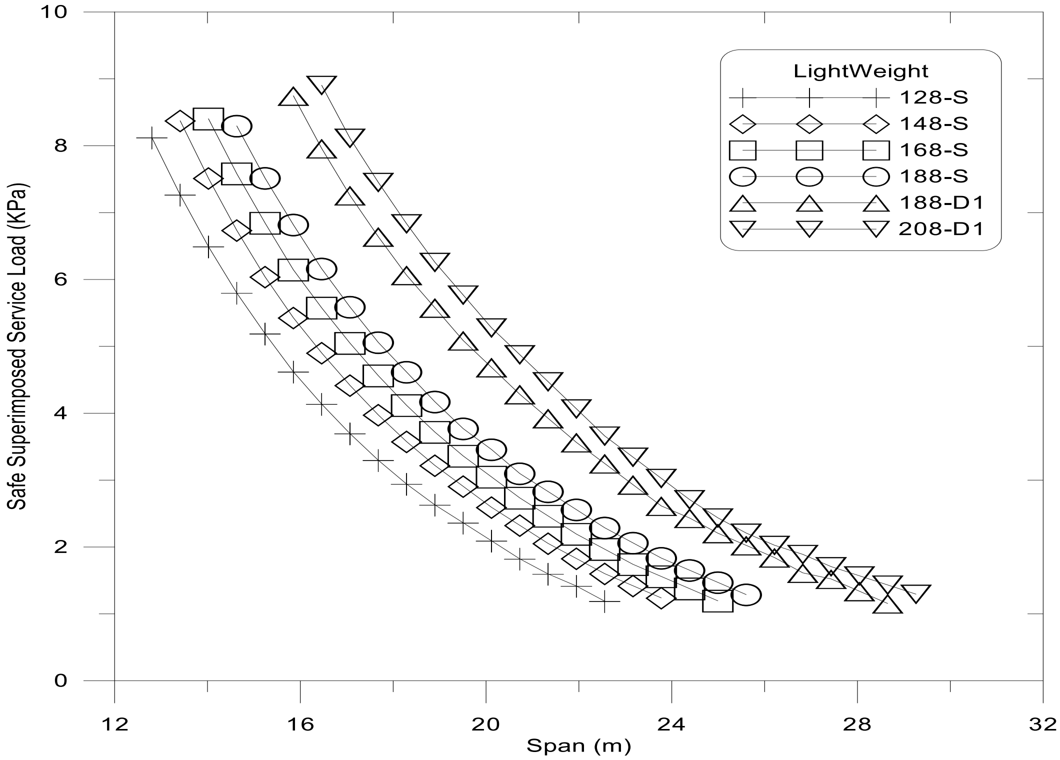

Fig. 3 Load-span charts for light weight DT beams

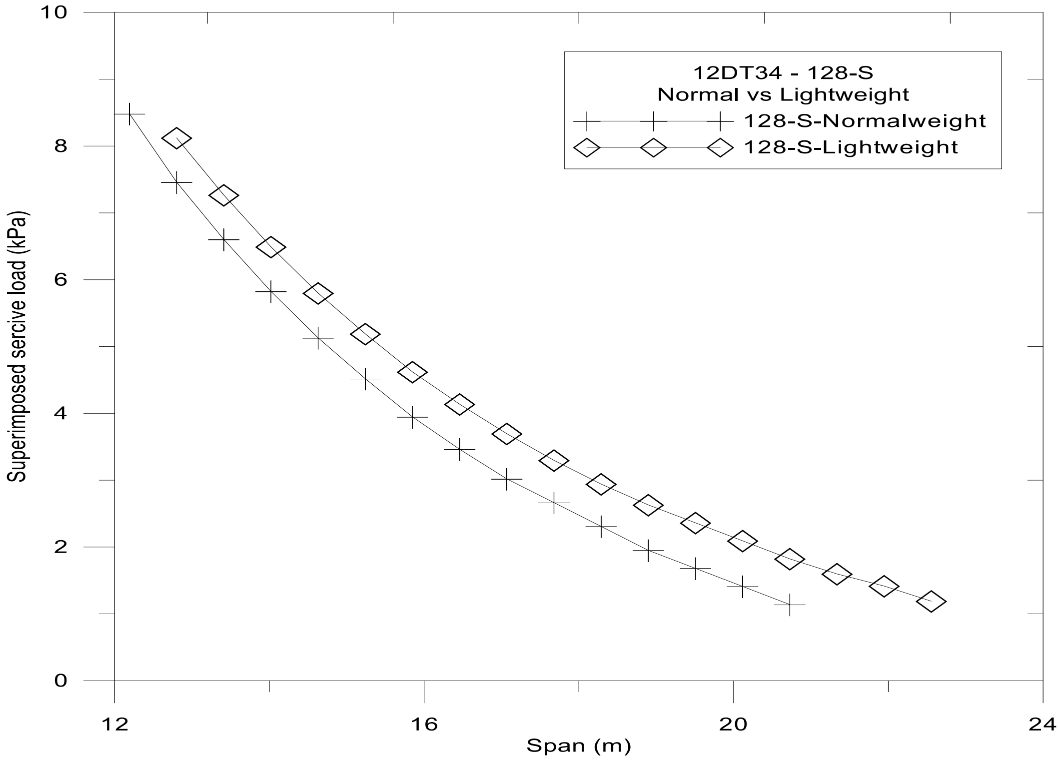

Fig. 4. 128-S Load-span comparison regarding different prestressing arrangement and amount

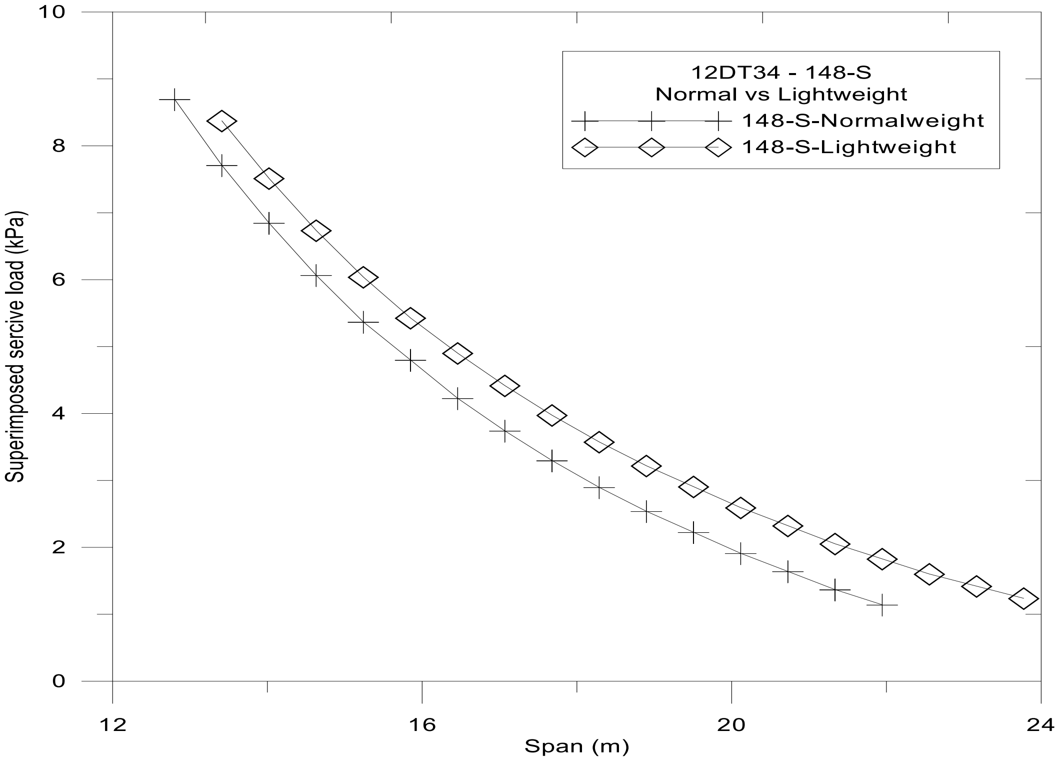

Fig. 5. 148-S Load-span comparison regarding different prestressing arrangement and amount

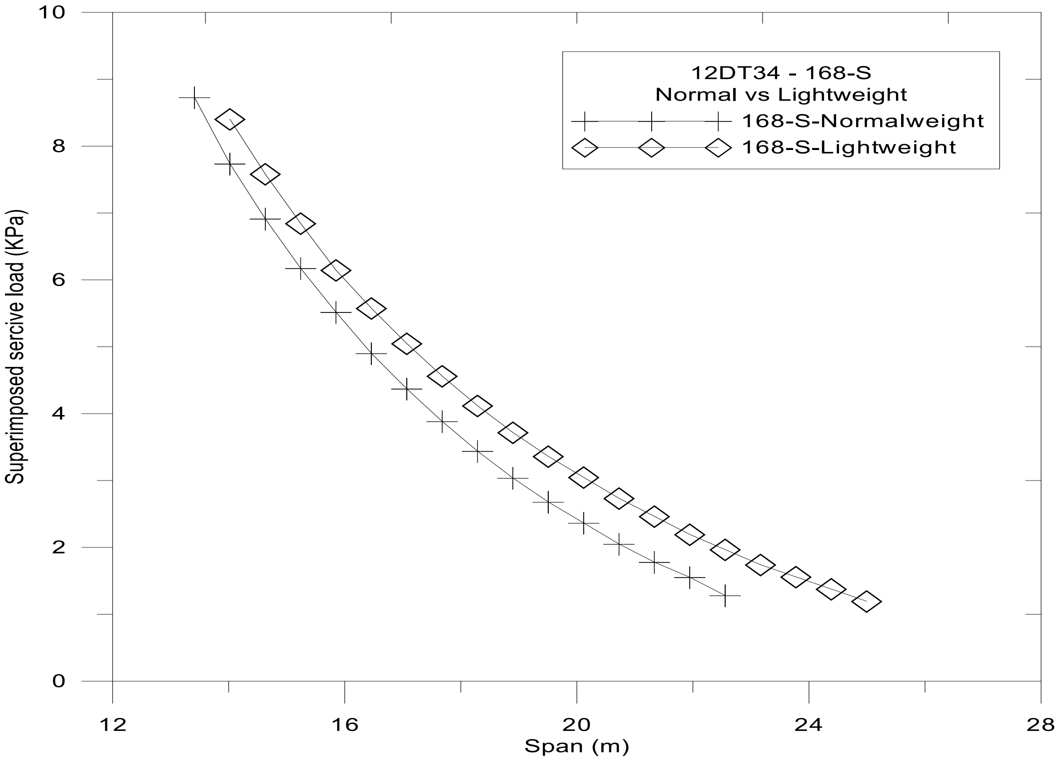

Fig. 6. 168-S Load-span comparison regarding different prestressing arrangement and amount

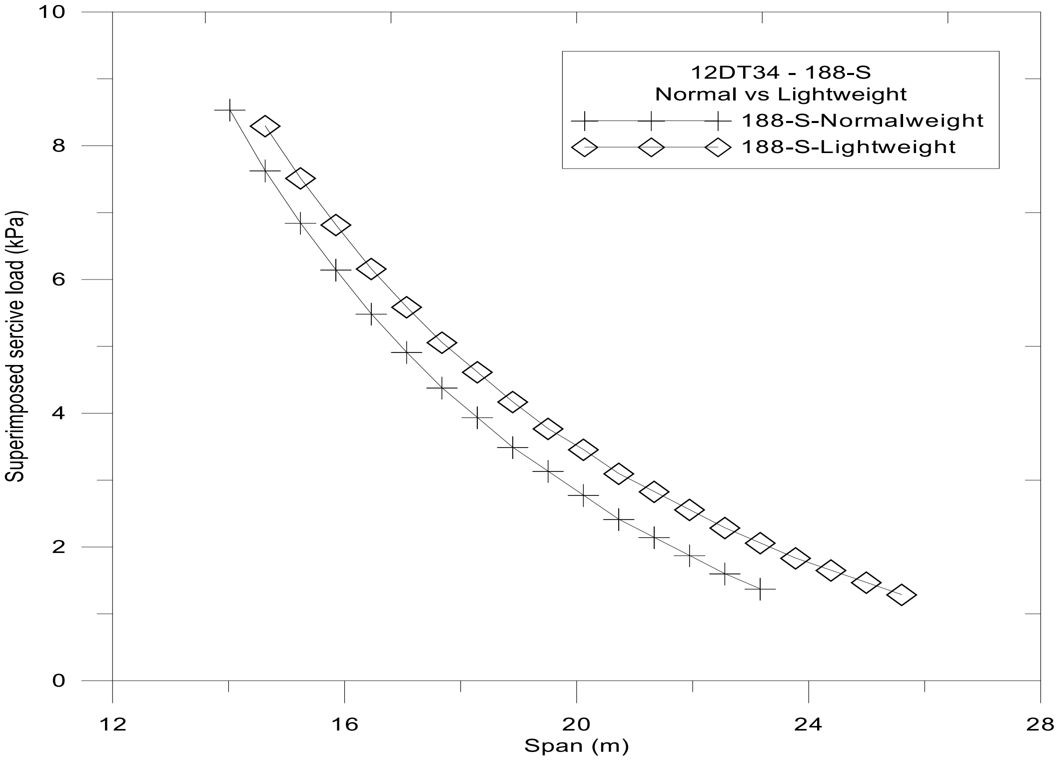

Fig. 7. 188-S Load-span comparison regarding different prestressing arrangement and amount

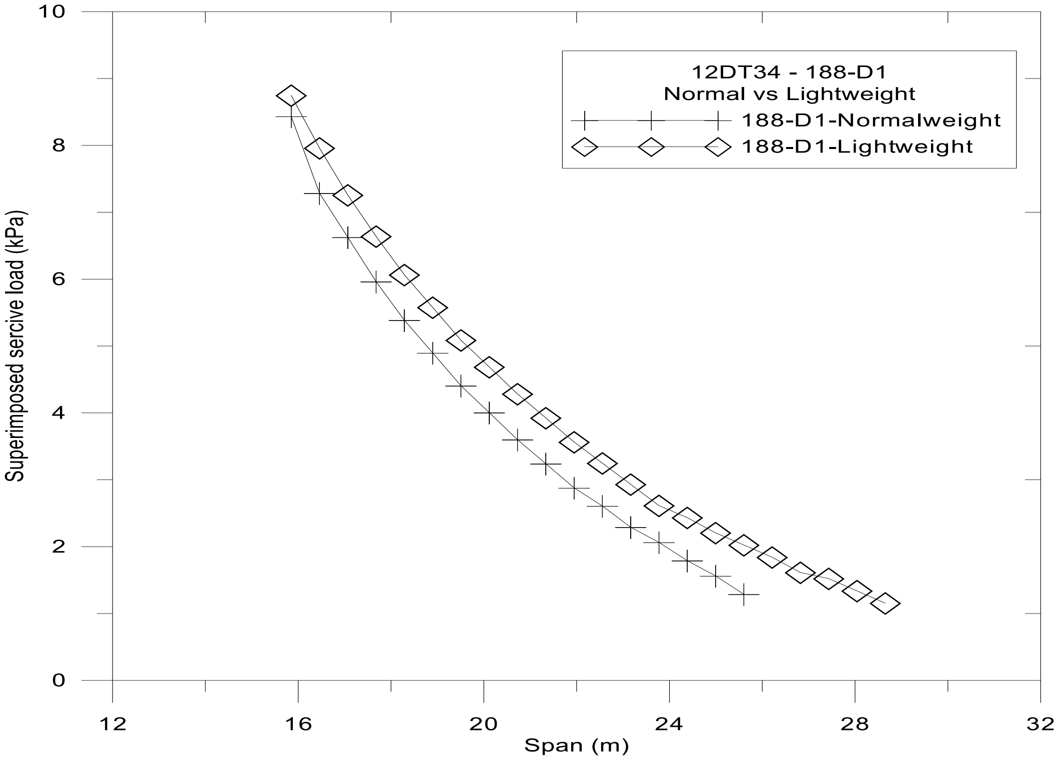

Fig. 8. 188-D Load-span comparison regarding different prestressing arrangement and amount

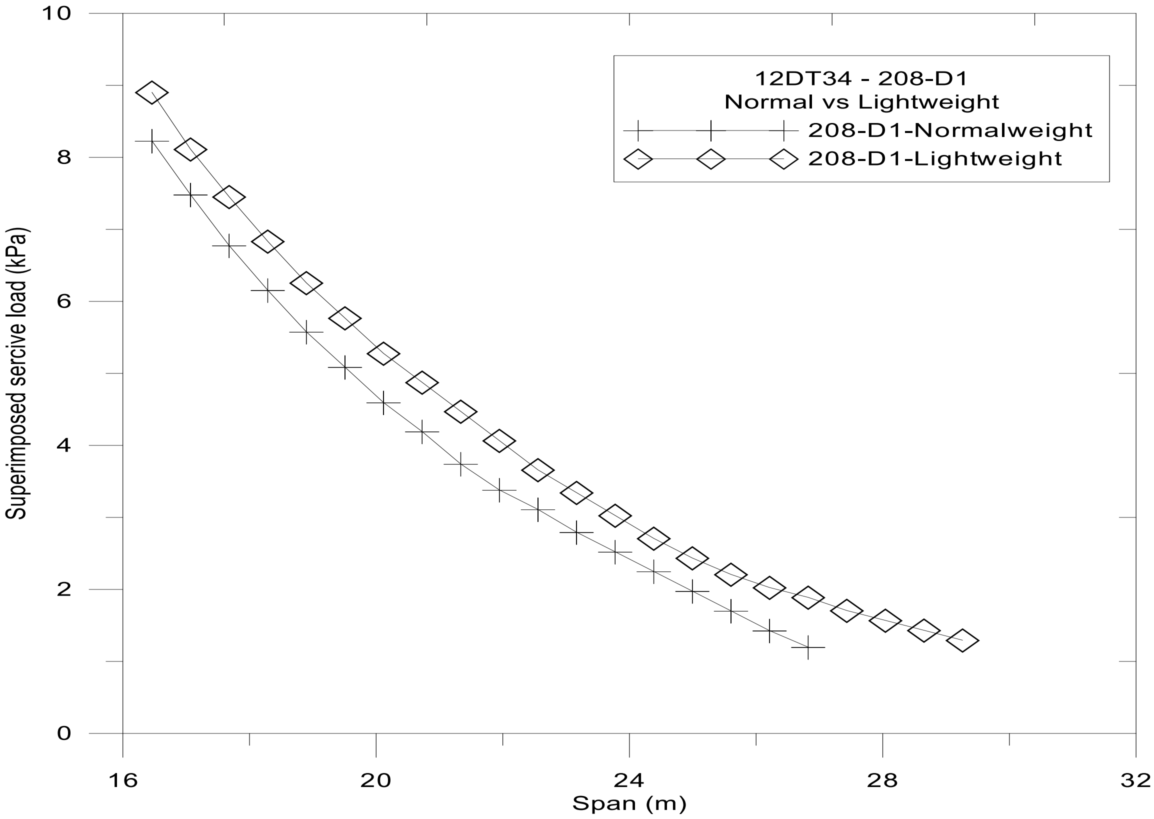

Fig. 9. 208-D Load-span comparison regarding different prestressing arrangement and amount

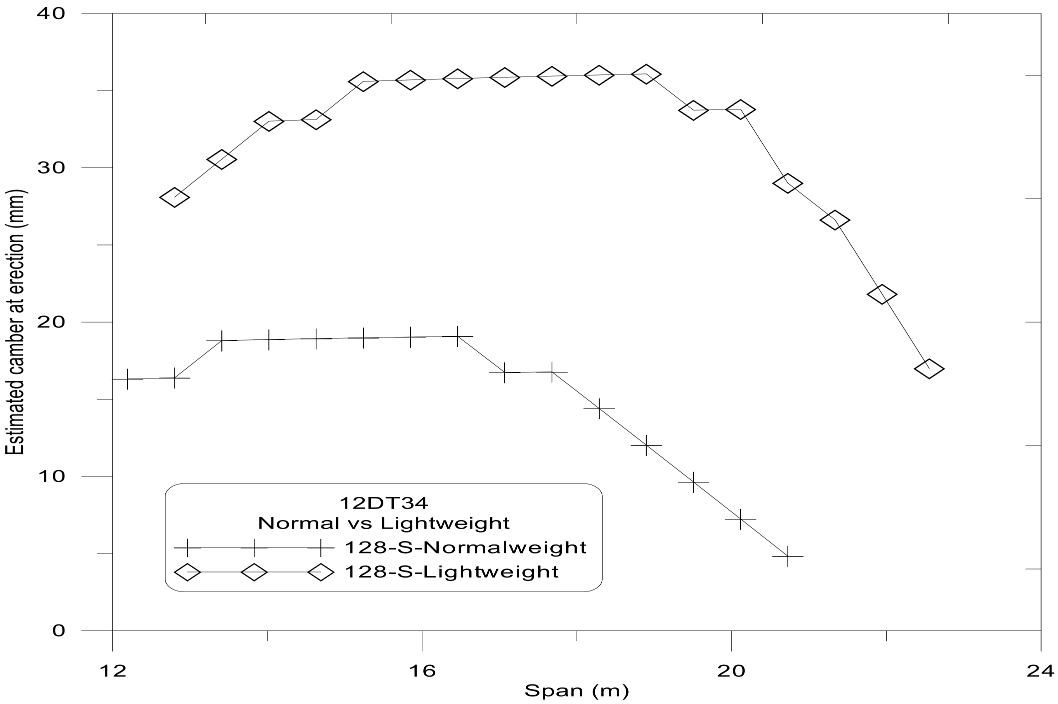

Fig. 10. 128-S Camber at erection comparison regarding different prestressing arrangement and amount

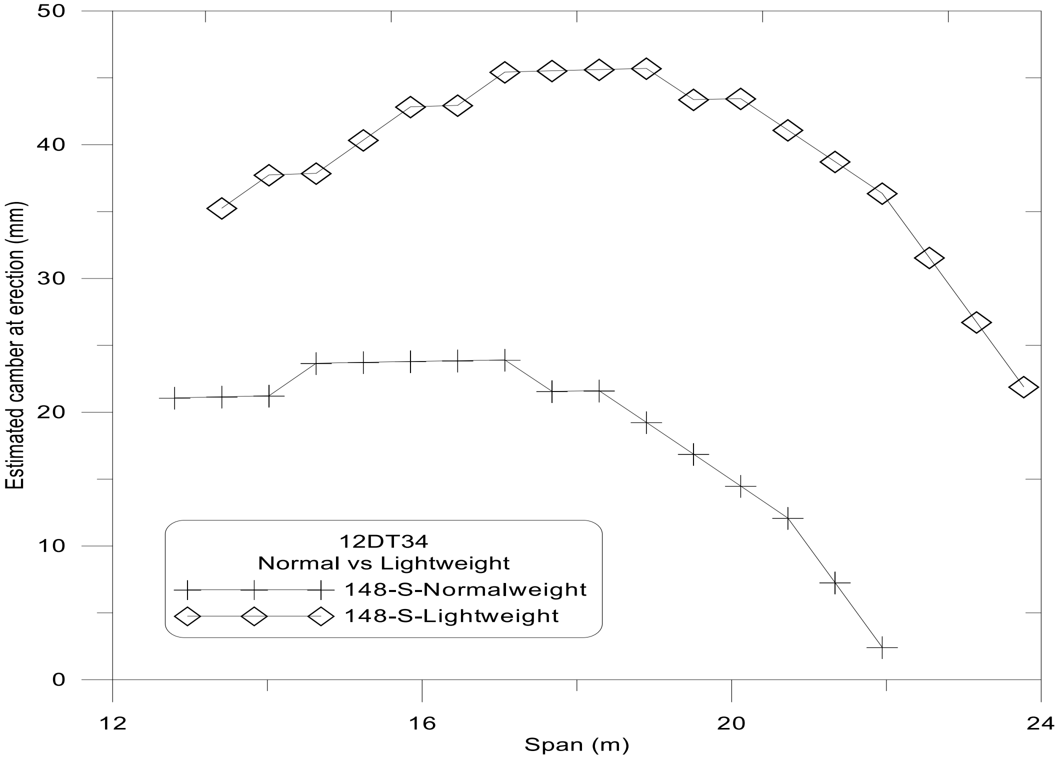

Fig. 11. 148-S Camber at erection comparison regarding different prestressing arrangement and amount

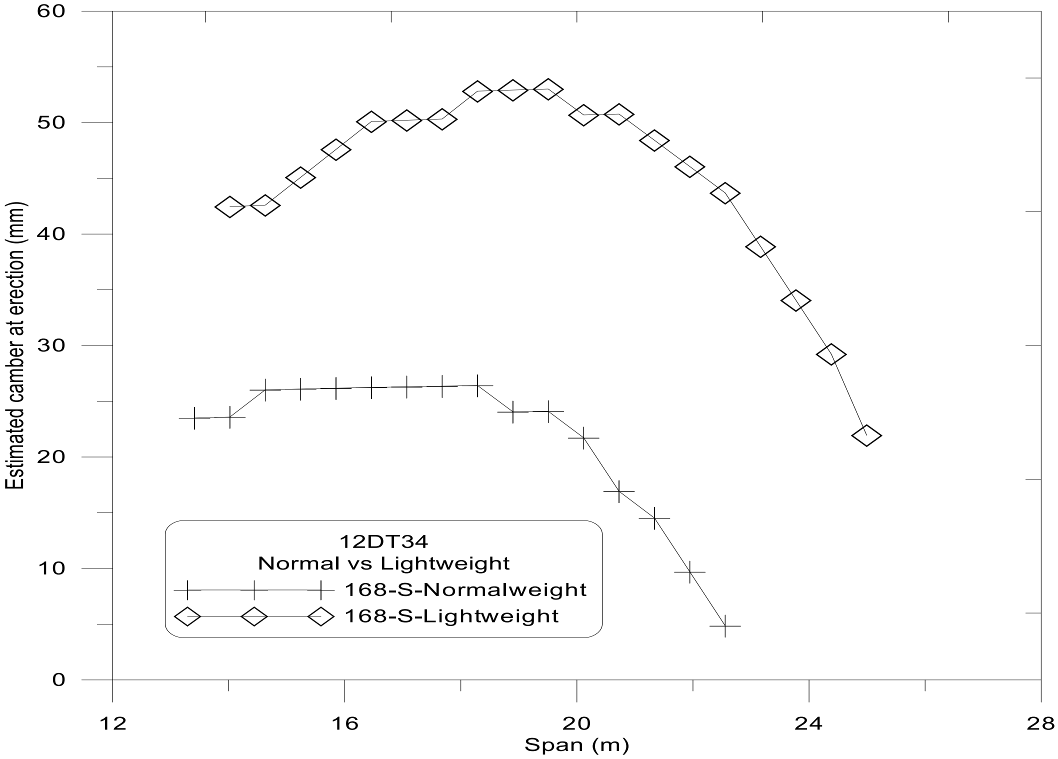

Fig.12. 168-S Camber at erection comparison regarding different prestressing arrangement and amount

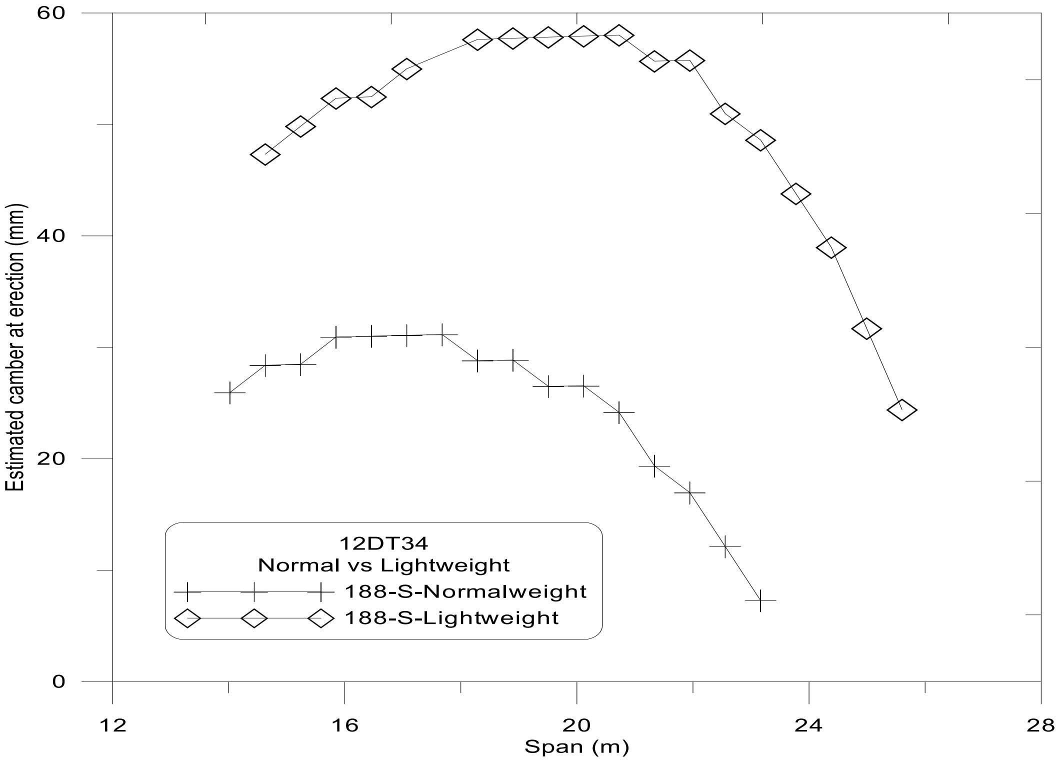

Fig. 13. 188-S Camber at erection comparison regarding different prestressing arrangement and amount

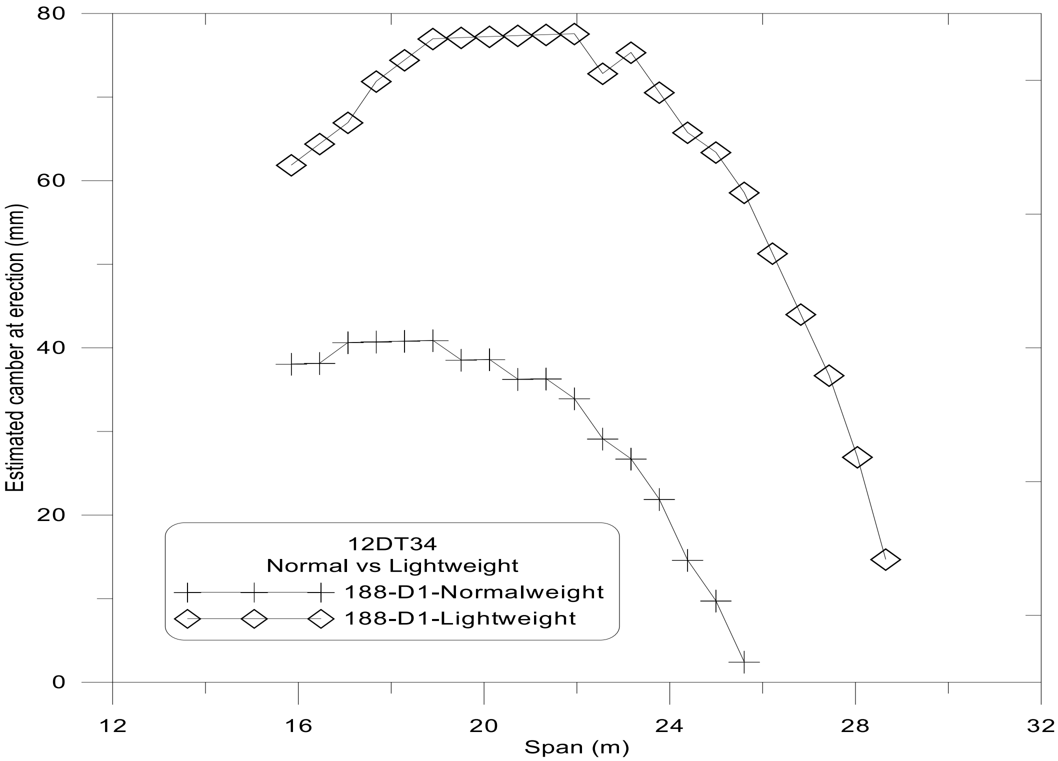

Fig. 14. 188-D Camber at erection comparison regarding different prestressing arrangement and amount

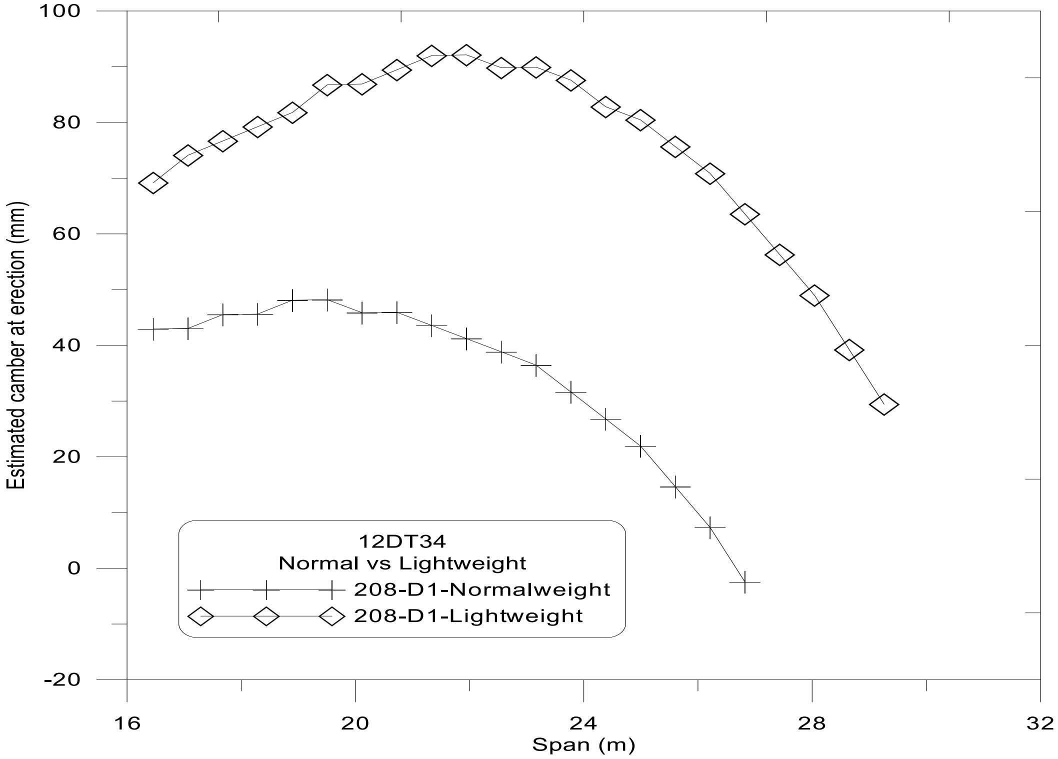

Fig. 15. 208-D Camber at erection comparison regarding different prestressing arrangement and amount

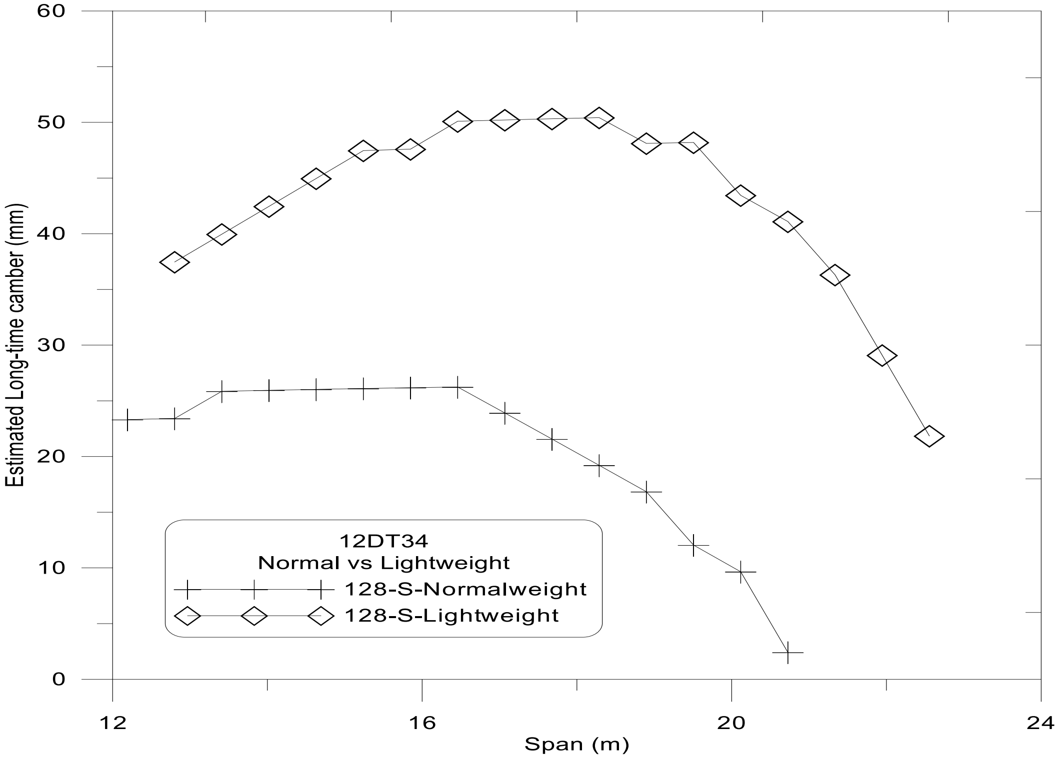

Fig. 16. 128-S Long-time camber comparison regarding different prestressing arrangement and amount

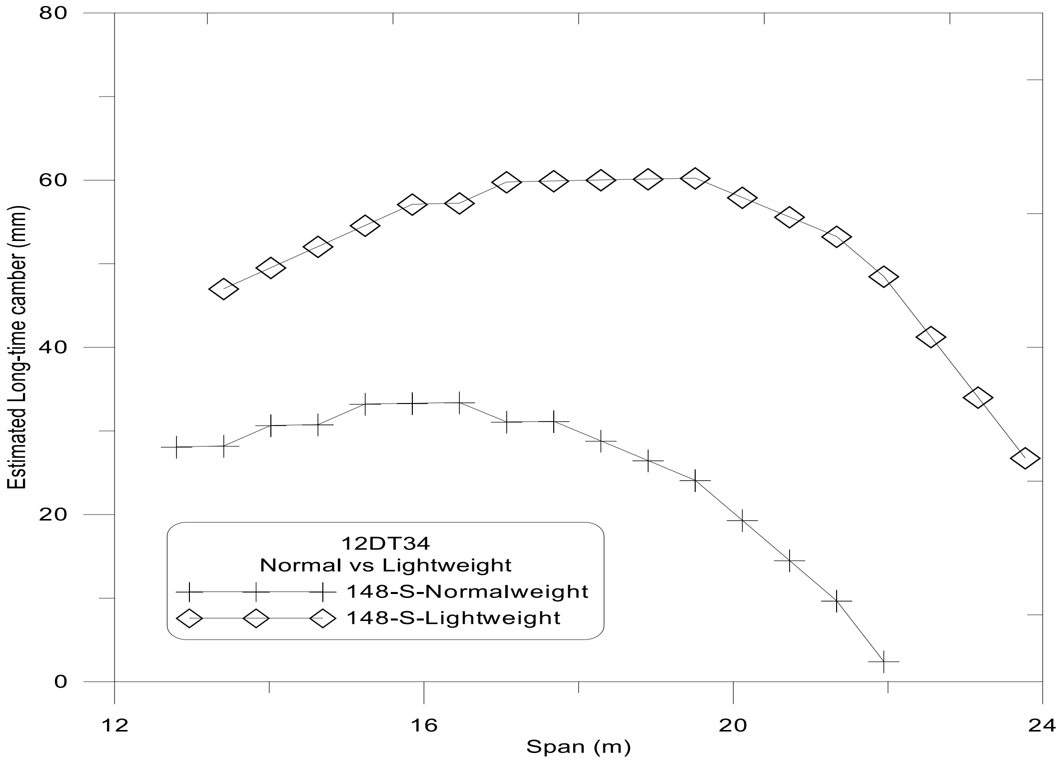

Fig. 17. 148-S Long-time camber comparison regarding different prestressing arrangement and amount

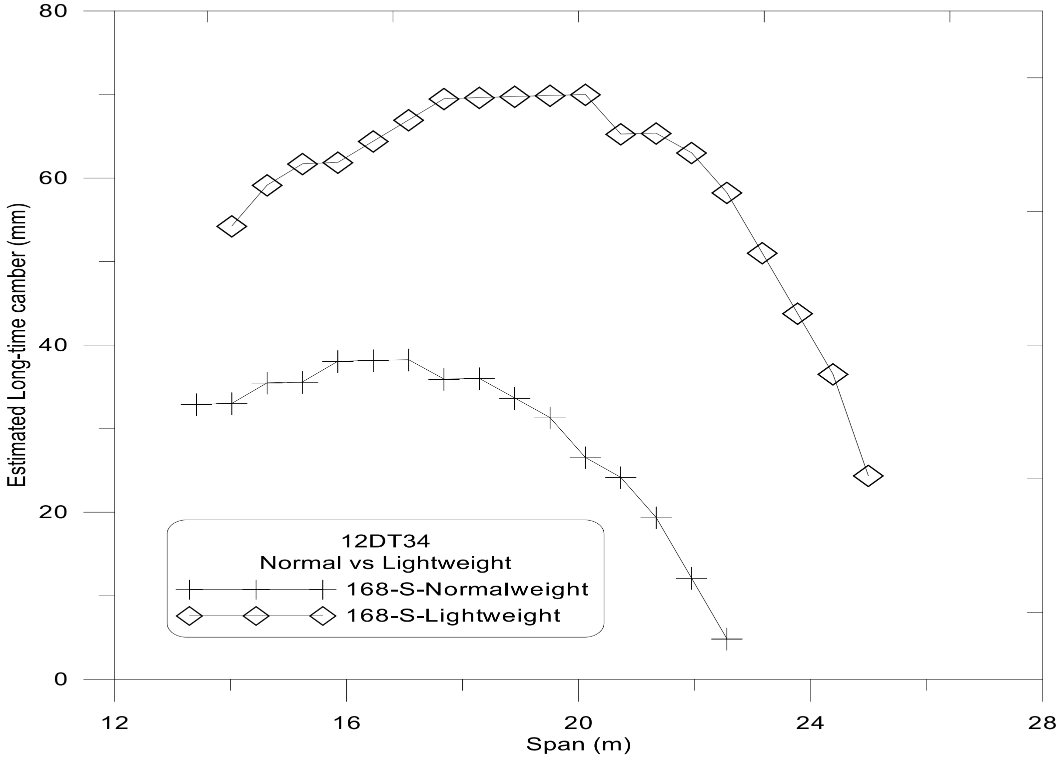

Fig. 18. 168-S Long-time camber comparison regarding different prestressing arrangement and amount

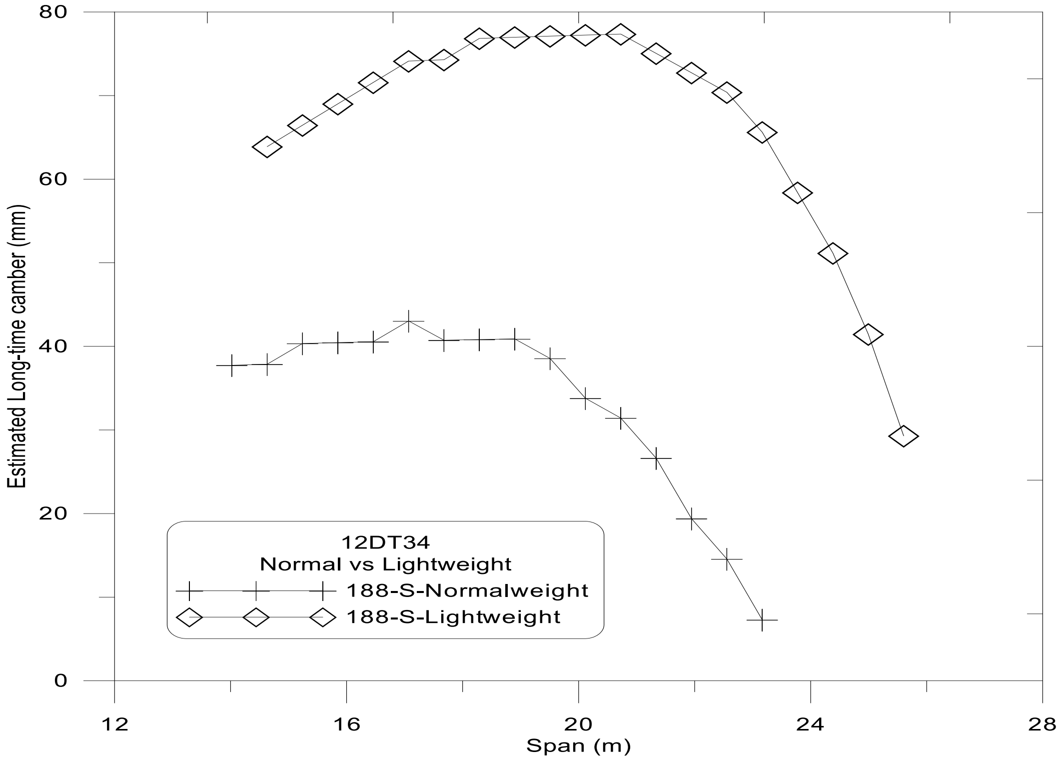

Fig. 19. 188-S Long-time camber comparison regarding different prestressing arrangement and amount

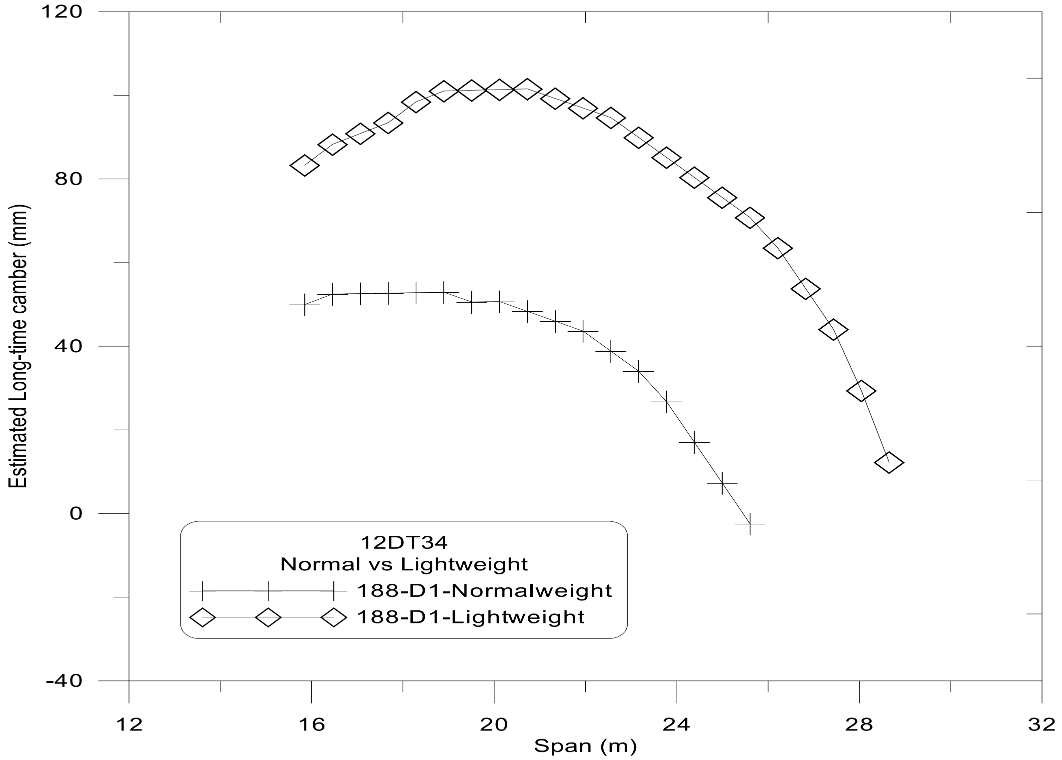

Fig. 20. 188-D Long-time camber comparison regarding different prestressing arrangement and amount

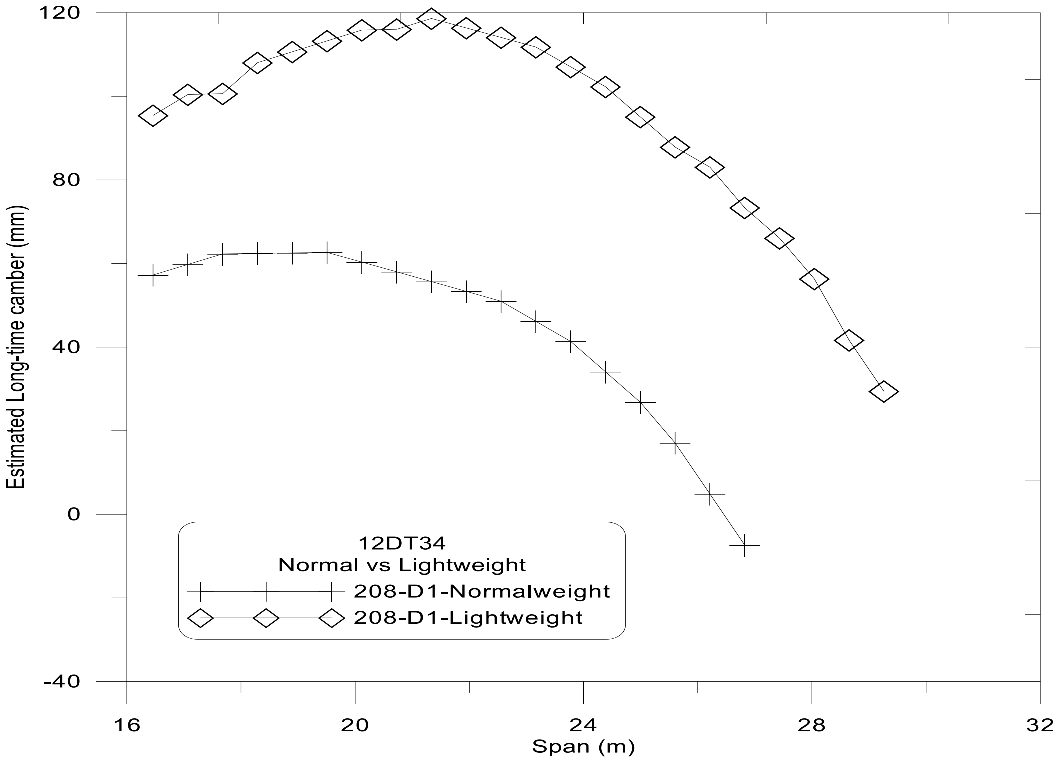

Fig. 21. 208-D Long-time camber comparison regarding different prestressing arrangement and amount

8. Conclusions

The conclusions of this study are:

1. Considering the benefit from the finite element technique as a active tool to simulate the full performance of either light or normal prestressed concrete double tee beams, where a several sets of numerical runs done to get a guidance in the designing double tee beams with wide range of variety in concrete weight and prestressing amount and arrangements.
2. The predicted behavior shown in load-span charts were the ability to cover more span by using lightweight concrete with respect to normal one. Also, clearly shown that the amount of prestressing could handle the situation by increasing its value to span more distance and take over the weight issue. For short span, the percent of increase range within 8-10%, while for long span the lightweight concrete double tee beam can carry more about 60%. Increasing the amount of straight prestressing tendons could help by increase the ability to carry more load for the same length with about 10-15%. While this percent jumped to reach 25-35% when the prestressing depressed at one point.
3. Using lightweight concrete could help to increate covering span up to 10% with respect to normal weight concrete, and that ration increase itself with increasing the amount of prestressing tendons to reach 14%. Same response shown when changing the arrangement of prestressing from straight to depressed tendon in one point, within that range.
4. Lightweight concrete double tee beam camber 7% more than normal weight for short span, while this values double to reach 6 times for long span. The overall response seems to be parallel along the variation of span length.
5. All charts for straight tendons range increasingly with almost closed range, but that range jumped to higher values when its change to depressed at one point that jumped to reach 33% increase in the same amount of prestressing numbers.

6. Variation for long-time camber, where almost within the same response the lightweight beams predict higher values and give better behavior with respect to normal weight concrete. Again, for short span the effect is much less than for long span, where its percent of increase start by 6% to reach 5 times.

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