International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878, Volume-8 Issue-3, September 2019

Design Aids for Prestressed Concrete Double Tee Beam with Web Opening Associated With the Variation of Its Compressive Strength

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***Abstract:** Precast prestressed concrete double tee beams are one of the most popular precast concrete floor framing system, which it's being from necessity to carry out many researche's studies to predict a powerful tool to simulate its full behavior. Herein, an investigating studies have been carried out to check the validity of increasing span length by increasing concrete compressive strength with the existence of web opening. The main advantage of these openings is that mechanical equipment can pass through the webs of double tees instead of under them. This reduces the floor-to- floor height and the overall cost of the building. Another advantage is a slight reduction in double tee weight that would improve the demand on the supporting frame both under gravity loading and seismic excitation. All of that advantage will be more benefit with larger span length, that will be limited within the existence of web opening. A numerical model was prepared checked to simulate the nonlinear behavior of prestressed concrete beams under monotonically increasing load. Within such numerical model, tested programs were made to predict longer span in considerable concrete compressive strength, that chosen from practical available values can be achieved in the site. After all of that a design charts were prepared to be a guide tool to engineers when double tee beams with web opening required to cover more span length. Curves are classified and presented considering the most common typical sections of the double tee beams modified to show the flexibility could be obtained when changing concrete compressive strength.*

I. INTRODUCTION

Prestressed concrete Double-Tees Tees are the perfect answer for development extends in which the quality, magnificence and adaptability of the plan are basic. Structures worked to cover long ranges and that require high load capacities with regards to floor and material frameworks are the ideal possibility for our precast and prestressed twofold tee solid parts, intertwined in a one of a kind "twofold tee" design that has better load bearing limits when thought about than empty center sections of equivalent length. Twofold tees include a level area (rib) and two stemmed vertical segments (networks). The blend of these highlights makes a basic part that can bolster high loads while likewise spreading over critical separations. This characteristic strength settles on twofold tees the best decision for building structures that highlight long ranges and that don't require extra roof wraps up.

Manuscript published on 30 September 2019
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Placing web openings in double tees allows mechanical equipment to pass through them, reducing the floor to floor height and overall building height. The reduced building height can result in the significant economy in the cost of the building
envelope and in the mechanical and electrical systems. A further benefit of weight reduction is savings in the supporting beams, columns, and a foundation due to both vertical gravity loads and horizontal seismic forces.This paper presents the results of research works that investigated the effect of increasing the compressive strength on the standard PCI double tee with web opening. Existing floor and roof framing systems were reviewed in addition to prior research on precast, prestressed concrete double tees with web openings. This analysis was used to design four full size specimens that were tested to failure chosen from literatures and an investigation works carried to obtain the largest span length depending on the factor of increasing concrete compressive strength.

II. LITERATURE REVIEW

The first published work on precast, prestressed concrete beams with web opening was conducted by Ragan and Warwaruk [1]. Since then, several other researchers have investigated prestressed concrete beams with web opening, including Suave [2], and Kennedy and El-Laithy [3]. Two of the more comprehensive studies conducted on prestressed concrete beams with web openings were done by Barney, Hanson, Corley, and Parmelee [4], and Kennedy and Abdalla [5]. Based on their research, both Barney et al [4], and Kennedy and Abdalla [5] developed design procedures for prestressed concrete beams with web openings.
Kennedy and Abdalla [6] have recently completed a comprehensive study of beams with one opening. They have proposed a rather involved procedure to design for the opening; however"," they have not consider simplification and possible standardization of beams with a large number of openings. Their paper gives a good discussion of the types of the cracking that can occur around an opening in a prestressed concrete beam and how these cracks form.
In 1996, Savage et al. [7]the tested experimentally four prestressed concrete double tee beams with the web opening under flexure, and then Hussam [8] carry a numerical investigation on the same prestressed concrete double-tee beam using finite element modeling, to obtain the effect of an existing web opining on the behavior of such beams under flexure. Hussam [9] also, on his PhD thesis study"," the behavior of the prestressed concrete double tee beam experimentally and numerically, where a program was prepared to analyze under flexure.

Results shows that the finite element's technique is a powerful method to simulate the behavior and follow up to failure.

III. CONSTITUTIVE RELATIONSHIPS AND FINITE ELEMENT FORMULATION

The *20-noded isoparametric brick element* was used to model the concrete"،" and both prestressing and reinforcing bars was idealized and axial members embedded within the concrete elements, as shown in **Fig. (1)**.

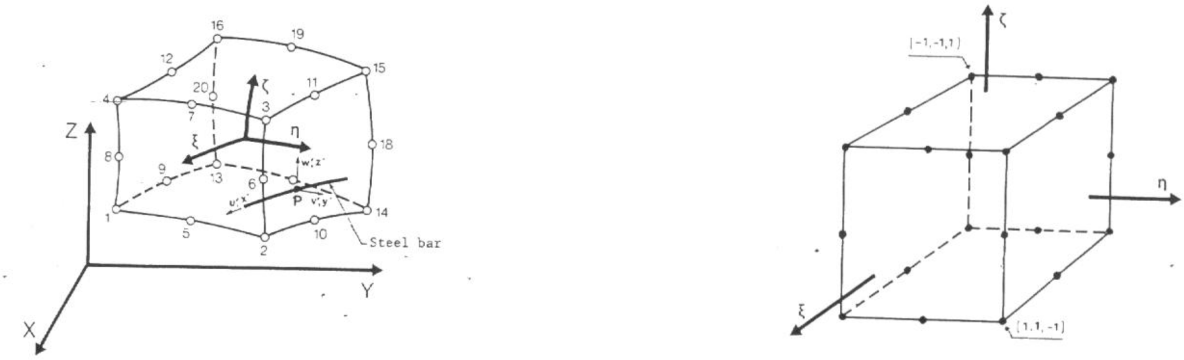

Fig. (1). The 20-noded isoparametric brick element [10].

The behavior of concrete in compression was simulated by an ***elastic-plastic work hardening model*** followed by a perfectly plastic response, which is terminated at the onset of crushing as shown in **Fig. (2)** [10]. In tension, a ***smeared crack*** model with fixed orthogonal cracks was used with the inclusion of models for the retained post-cracking stress and reduced shear modulus as shown in **Fig. (3, and 4)**.

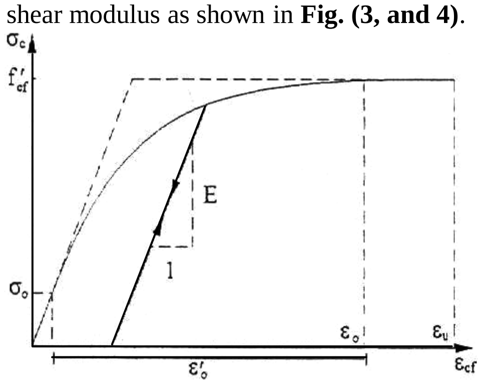

Fig. (2).The Uniaxial stress-strain curve for concrete [10].

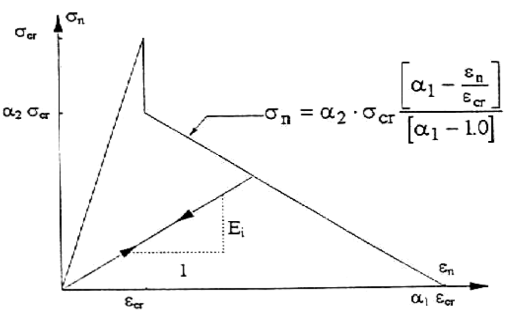

Fig.(3).The Tension-stiffening model for concrete [10].

The nonlinear equations of equilibrium were solved using an incremental-iterative technique operating under load control. The ***standard and modified Newton-Raphson*** methods were used as solution algorithms [10].

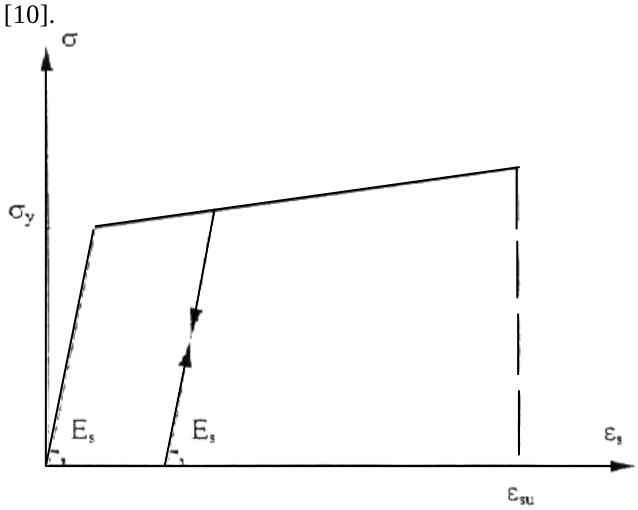

Fig. (5).The Stress-strain relationship of steel bars used in the analysis.

For full details of the constitutive models and the finite element formulation adopted in this research work can be found in reference [9]

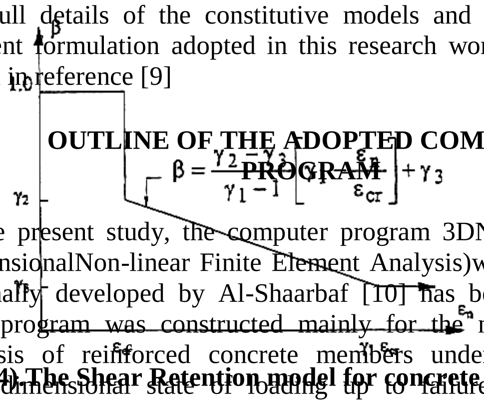

Fig.(4).The Shear Retention model for concrete [10].

IV. OUTLINE OF THE ADOPTED COMPUTER PROGRAM

In the present study, the computer program 3DNFEA (3-DimensionalNon-linear Finite Element Analysis)which was originally developed by Al-Shaarbaf [10] has been used. This program was constructed mainly for the non-linear analysis of reinforced concrete members under general three-dimensional state of loading up to failure. In this study, the computer program 3DNFEA has been adopted in analyzing prestressed concrete beams.

V. HUSSAM DOUBLE TEE BEAM ANALYSIS

In 2010, Hussam [8] published a conference paper, where a numerical analysis carried out on Savage et.al [7]

ISSN: 2277-3878, Volume-8 Issue-3, September 2019

prestressed concrete double tee beams, where Savage test experimentally set of beam to study the effect of existing web opening on the behavior of such beams. Our target herein is to used the control beam designated as 7G1, which is without web opening, so an additional parametric analysis will done to study the effect of increasing the compressive strength to achieve more span length, within the use of other testing sample 7G2, 7G3, and 7G4, a first comparison will be after increasing concrete compressive strength and span more distance. Savage beams were prismatic members of a typical production spanning 13.7m, where that length need to be increased. The beams may serve as units in roofing/flooring parts or constructing parking structures.

5.1 GENERAL CIRCUMSTANCES OF SAVAGE ET AL. DOUBLE TEE BEAMS

Savage [7] chose double tee beam with span of 13.7m for his research and Hussam [8] analyzed the same beam and give design load-chart table for limited span length. All beam tested was use in office construction, therefore the used loading was an office live loading of 245kg/m^2 plus a 100kg/m^2 superimposed dead load plus 122kg/m^2 to present in50mm topping.Which about 465kg/m^2 total superimposed uniform service load and 730kg/m^2 an ultimate load.

In order to better transfer stress from the flange to the web, 50mm of concrete was left between the top of the opening and the bottom of the flange. Based on the required cover of the strands and any mild steel reinforcement required. The maximum opening depth could be 330mm as shown in Fig. (6). With 330 deep openings, there were high compressive stresses in the bottom chords at transfer and high tensile stresses at service. Savage consider the opening based on the limitation of flexural cracking ACI 318-02 sec. 7.7.3.2. where the final opening size used was 300×900mm. Savage et al. initially considered several different shapes for the web openings, including ellipses, rectangles, hexagons, and circles. Herein rectangular openings were adopted for the analysis. In final five openings between depression points where created. And another additional opening was placed at each end of the tee outside of the depression points.

Concrete strength between 41 and 69MPa were considered. The finite element analysis showed that higher concrete strength of f_c'=48MPa and f_{ci}'=38MPa was required.

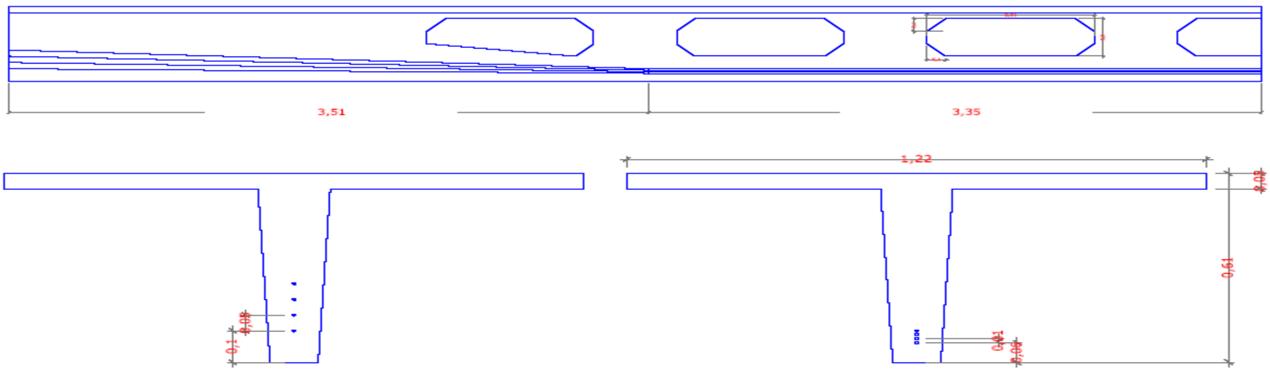

Fig.(6). Precast section dimensions and prestressing details [8].

5.2 DESIGN CONSIDERATION

The fabrication of tees and location of indicated positions for replacing concrete were shown in Fig. (7), where Tee 7G1 was design as a solid tee in order to compare the behavior the modified tees Tees 7G2, 7G3, and 7G4 each had seven replacement locations. A combination of Finite element modeling and design procedure followed by Hussam [8] was adopted to design the tested tees. The materials used.

All test specimens were identical except for additional reinforcement around the location where concrete aimed to be replaced.The Same technique adopted by Hussam [8] for strengthen the location of web openings. The strands were all stressed to *0.75* f_{pu}. The concrete used had an f_{ci}'=38MPa and an f_c=48MPa. All shear reinforcement used in the finite element model by Hussam [8] where repeated herein, and the same technical data used.

VI. FINITE ELEMENT IDEALIZATION AND MATERIAL PROPERTIES

By taking into consideration the advantage of geometric and loading symmetry, a segment which represents one quarter of the beam has been used in the finite element analysis. The chosen segment was modeled using the 20-node isoparametric hexahedral brick elements. This quarter was discretized into 74 brick elements. The uniformly distributed load was modeled using equivalent nodal loads distributed at the top face of the flange. The finite element mesh, boundary and symmetry conditions, shown in Fig. (8).

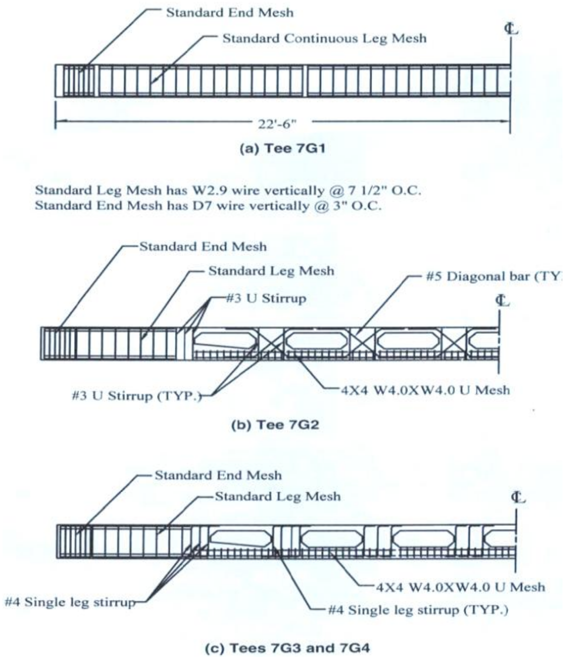

Fig.(7).Savage et Al .The Beam – Reinforcement Detail of specimens

The modelled concrete used Young's modulus equal 27600 N/mm^2, and Compressive strength f_c' equal 48MPa, at the same time"،" Tensile strength f_t considered 4.1MPa, and Poisson's ratio,

5.3

□□□□ =0.2. While for Prestressing tendons Young's modulus used 200GPa, and the Effective prestressing stress considered 950MPa and the Yield stress equal to 1860MPa The finite element analyses have been generally carried using the 27-point rule, with a convergence tolerance of 4%. The modified Newton-Raphson method in which the stiffness matrix is updated at the second iteration of each increment of loading has been adopted as a nonlinear solution algorithm. Non-uniform increments have been used applying external loads. Large increments were used at the first five stages of loading, and then appreciably smaller increments were used for stages close to the ultimate load

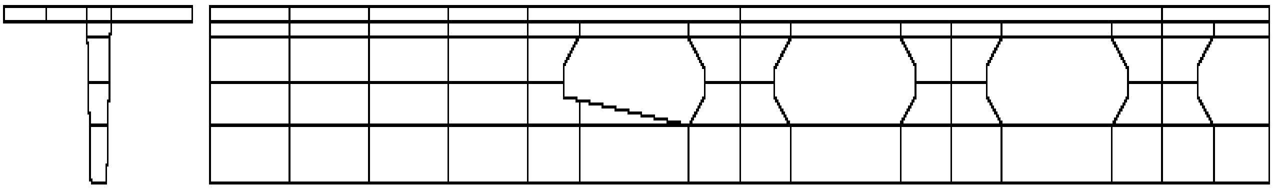

Fig.(8).Savage et Al .The Beam – Mesh refinement 56 brick element.

5.4 Beams- Results of Analysis

Numerical analysis predict the full behavior of the tested experimentally beams and moment-deflection curves were plotted for all of the tees as shown in Figs.(9-12). The tees displaced identical behaviour in the service load region, but the curved diverged after the point of cracking., which is acceptable.

The concluded behaviour was identical between the control beam without web opening and with other tested beam with web opening when the concrete within first uncracked stages. The figures reveal good agreement of the finite element solutions obtained for both beams 7G2, 7G3, and 7G4, compared with the experimental results throughout the entire range of behaviour. Also, the figures indicate that the numerical and experimental responses are very close within the elastic stage. After that the nonlinearity commences and the method of simulation becomes more important. This causes slight differences in ultimate carrying capacity.

The shown leak between the resulting behaviour is due to the accuracy of measurement, where in practical experimental case, the recording of the deflection and the method of calculating the moment capacity is less precise with respect to the numerical once.

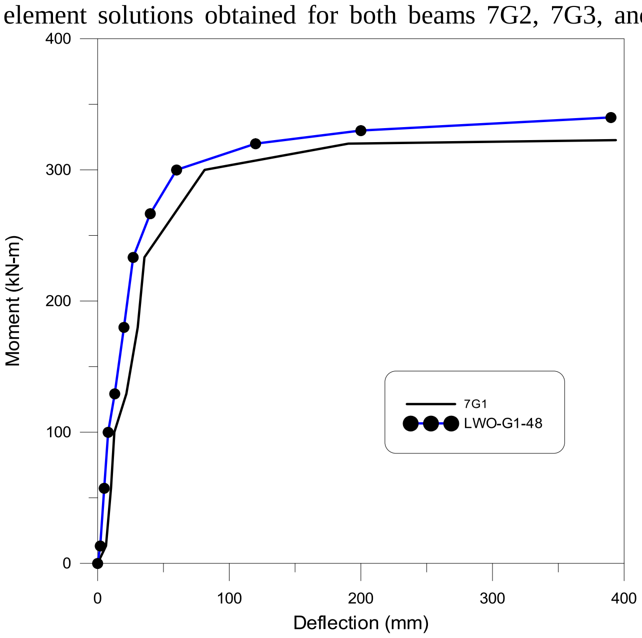

Fig.(9).7G1- mid-span moment-deflection behavior.

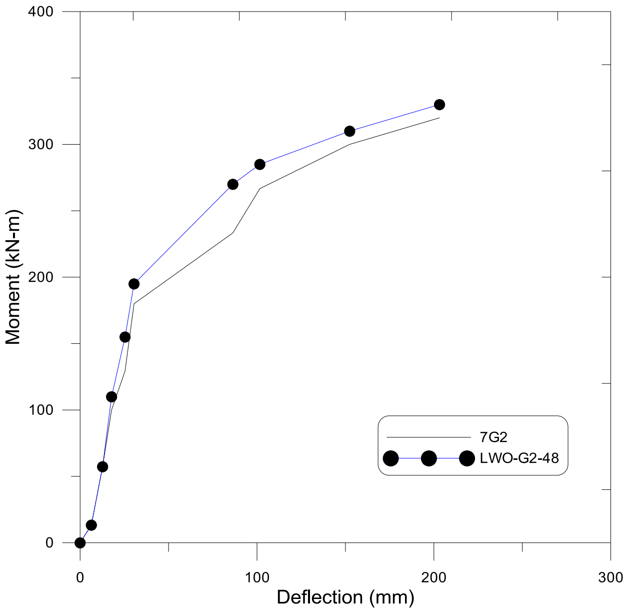

Fig (10).7G2- mid-span moment-deflection behavior.

Retrieval Number E1921098319/2019©BEIESP
DOI: 10.35940/ijrte.E1981.098319
Journal Website: www.ijrte.org

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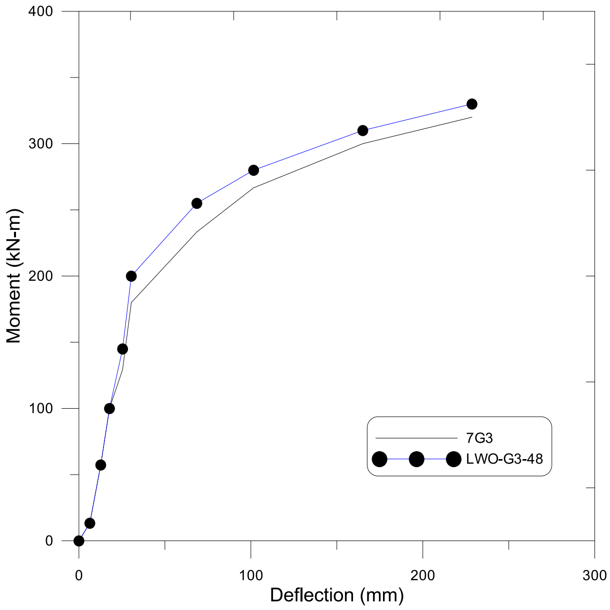


Fig.(11).7G3- mid-span moment-deflection behavior.

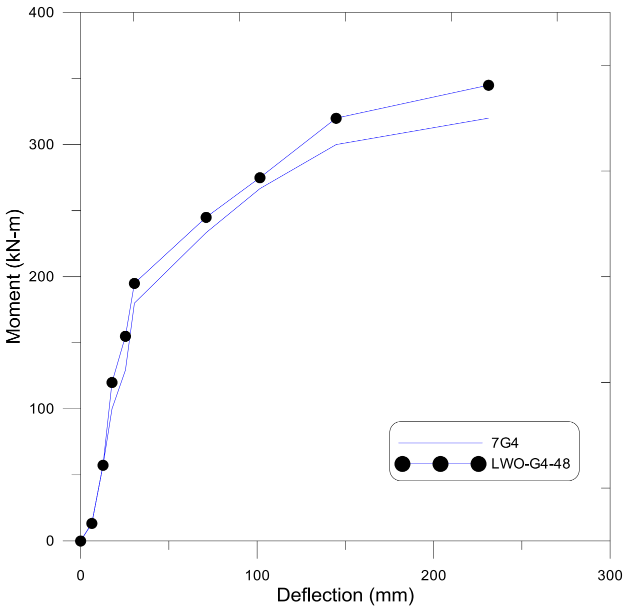


Fig.(12).7G4- mid-span moment-deflection behavior.

5.5 Effect of increasing Concrete compressive strength

Within changing the compressive strength of the chosen tested numerically double tee beams, the behavior show good improvement and the overall carrying capacity increased as shown in Figs.(13-16).The solid tee, Tee 7G1, failed due to crushing of the concrete near the quarter points of the tee. Tee 7G2 failed due to the simultaneous crushing of the concrete at between the quarter and the third points at each end of the beam, in a manner similar to the solid tee crushing. Tees 7G3 and 7G4 both failed when the prestressing strand fractured below the opening at mid-span. It does not appear that any of the tees failed prematurely due to stress concentrations caused by the web openings.

Beam 7G1 shows an increase in its moment carrying capacity, where the increase raised within the value of the compressive strength increase as shown in the Table (1). A comparison between the ACI method of calculation the moment carrying capacity and the results obtained from the Finite Element Method. The results show that the finite element method more conservative than ACI provision, where it's appear that a 2% higher at lower strength raised to 5% at high strength concrete. Generally that in its role helped to span more length. Where the designer used this important factor to develop the double tee by increasing its span length and retested again numerically. Within this procedure, the design charts were prepared.

Almost, the developed new double tee beams with shows similar behavior at the first stages up to its cracking points, after that the variation start to improve and the moment carrying capacity increase relatively. Higher compressive strength shows rapidly improvement, where concrete with 90MPa compressive strength jumped to 15% higher the control 7G1 beam [17, 18].

The Table (1) Moment capacity variation due to compressive strength increases

f_c' (MPa)	M_{ACI} (kN.m)	$M_{(F.E.M)}$ (kN.m)	$M_{(F.E.M)}$ / M_{ACI}
48	336	340	1.01
55	343	350	1.02
65	346	360	1.04
75	349	370	1.06
90	351	390	1.11

Beam 7G2, shows more ductility than the control beam 7G1 as the show in Fig. (14). That appear on it's allowing for more deflection at its mid-span. About 47% more flexibility are provided by increasing the compressive strength from (48MPa - 90MPa). Also, the moment carrying capacity does increased by about 35% within used high strength concrete.

The Figure (15 and 16) drawn for the behavior of Beams 7G3, and 7G4 where they being almost similar way behave. Beams tested shows little ductility The High strength concrete (C90) show more higher a performance in beam 7G4, where its values increased more effectively than a lower one (C75).All beams followed the same response and move in identical behavior at its first stage where the concrete at uncracking stage, after that, the compressive strength effect appear and start to control the overall beam resistance and capacity.In general, the beams with high strength concrete shows higher response and its can developed its strength capacity much more than a low strength concrete, allowing the designer to increase the span length too much more value, where that was the main goal of this research study.

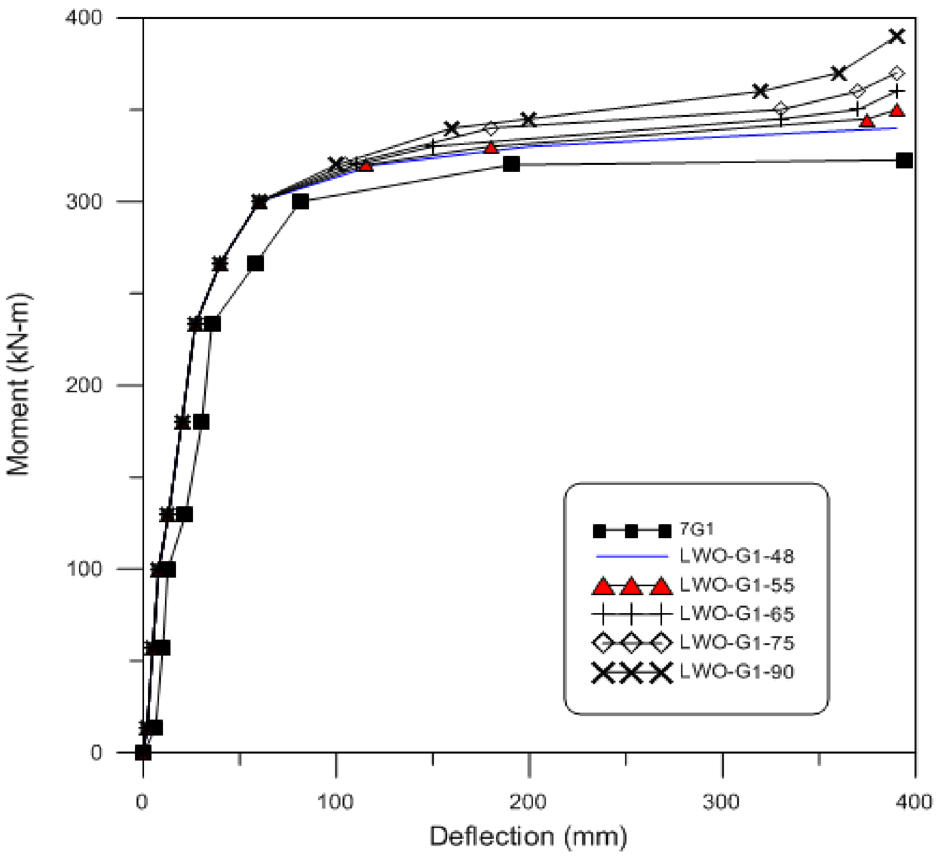


Fig. (13) Beam 7G1- Effect of increasing concrete compressive strength

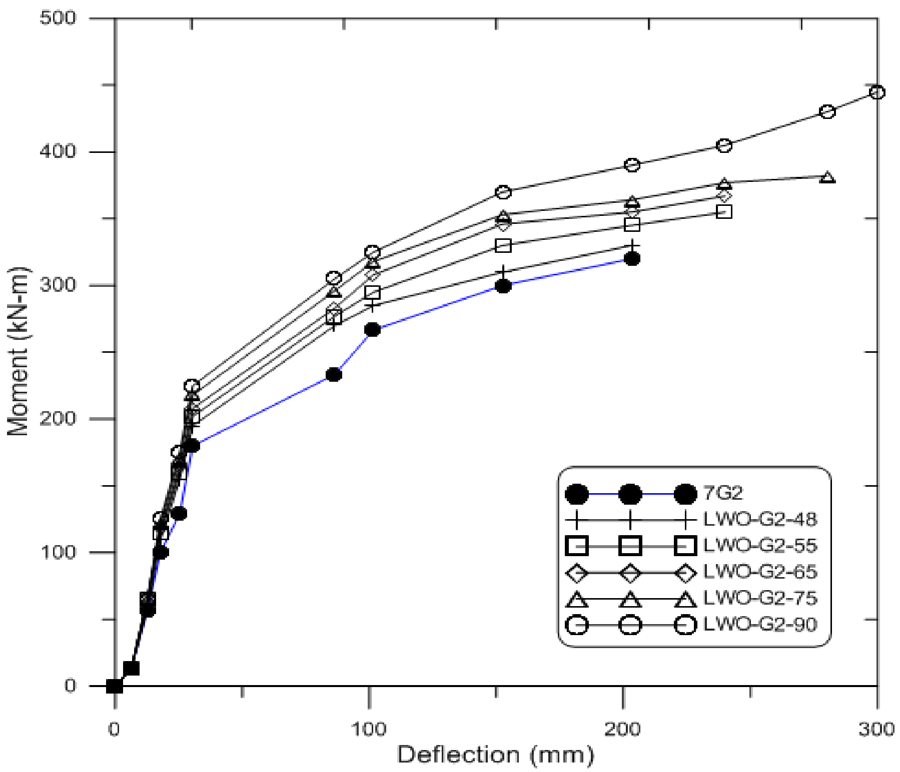


Fig. (14) Beam 7G2- Effect of increasing concrete compressive strength

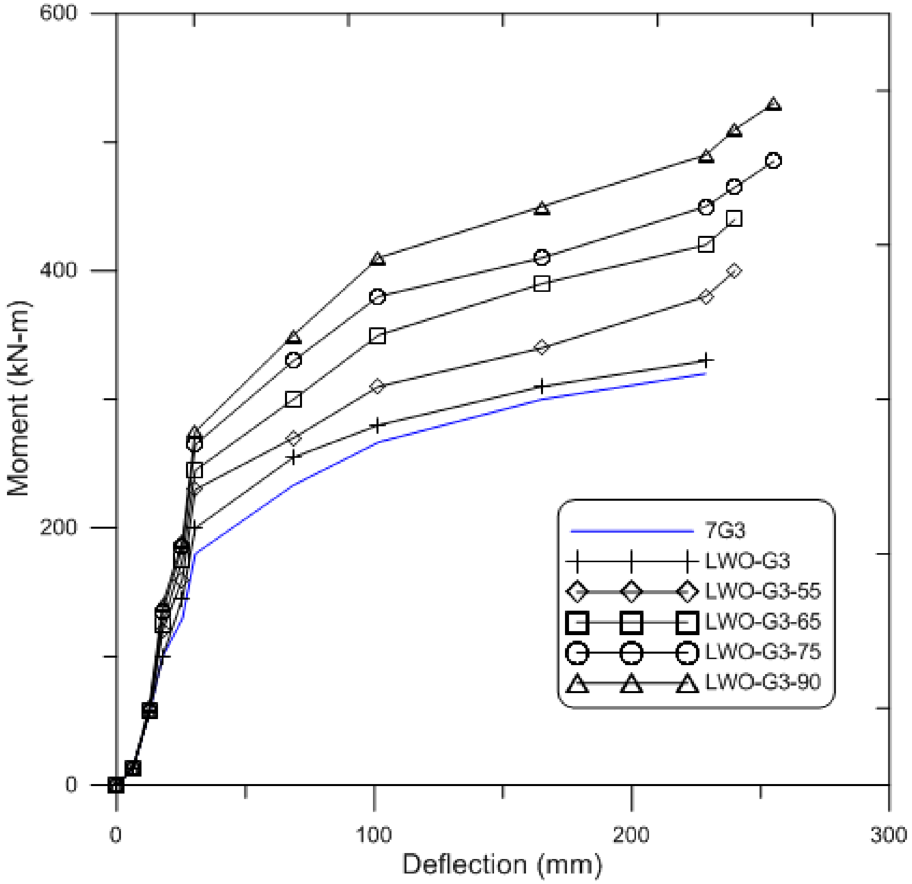


Fig. (15) Beam 7G3- Effect of increasing concrete compressive strength

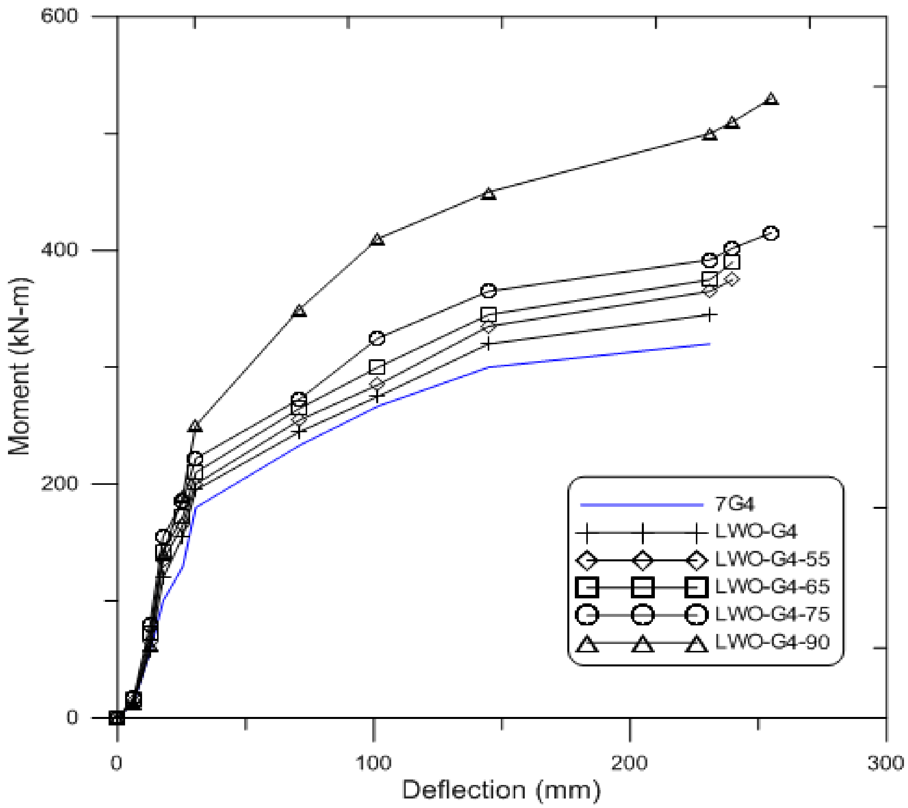


Fig. (16) Beam 7G4- Effect of increasing concrete compressive strength

VII. SPAN-LOAD CHARTS FOR PRESTRESSED CONCRETE DOUBLE TEE BEAMS

A large number of computer runs using the finite element technique was made to produce curves that give a handy help for simple and fast design of prestressed double tee beams under flexural service and ultimate loads. Curves are classified and presented considering the most common typical sections of the double tee beam. The function of the double tee member in practice is almost as either floor or roof, that limit the type of loading on be uniform distributed over the full span. On that base all loading obtained from these data are considered uniformly distributed.

6.1 Description of the chosen beam

Figure (17) shows the over all section dimension. This beam was tested numerically for different lengths starting from 6m span to 45m span. The support condition is fixed to the pin-roller case, and the loading considered is uniform distributed over the entire beam span.The **Table (2)** gives the general section and material properties.

The Table (2) Double tee material properties.

Section properties	Material properties
A = 318063mm^2	f'_c = 45MPa
I = 1.73×10^{10}mm^4	f'_{ci} = 38MPa
Y_b = 522mm	f'_{ct} = 215MPa
Y_t = 239mm	f_{pu} = 1860MPa
W = 7.5 kN/m	W_c = 23.5 kN/m^3
12.7mm LR Strands	

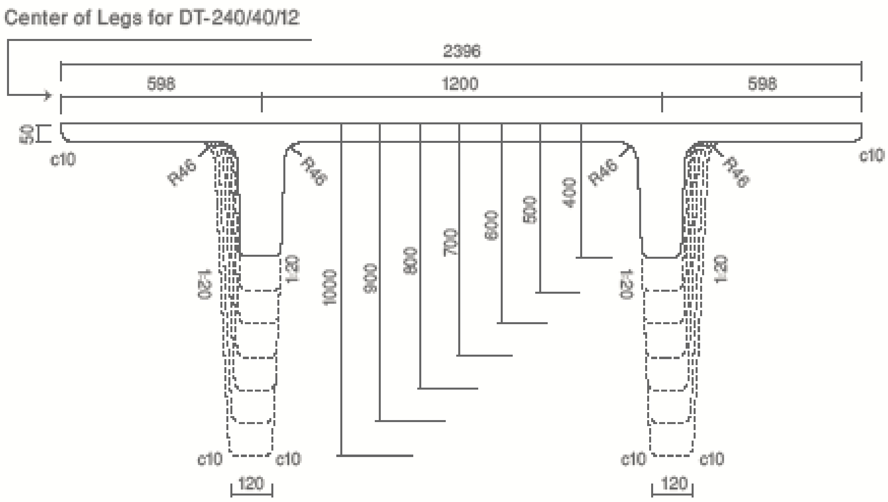
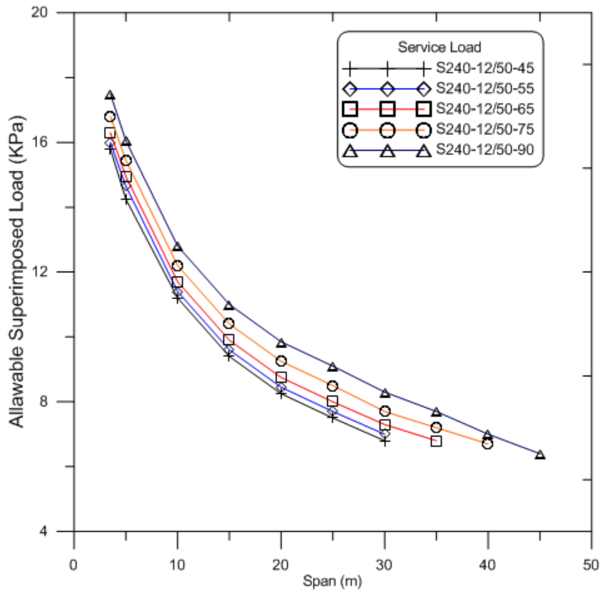


Fig. (17). Section dimensions (all dimension in mm).

6.2 Design Charts

First, one may consider a span length of about 6m with the above characteristics, to start the design and recheck process by using the finite element method and in each time a various compressive strength checked. Considering all data adopted and listed in Hussam [8], specially the number of strands and layout of additional reinforcement. Because within the increase of span length, more wire strand need and addition overall effective stand force must be applied.

Load Tables included herein were derived from computer-calculated data, are intended as aids to preliminary sizing, and must be interpreted using sound engineering judgment. These Span-Load Tables present precast double tee with web opening as indicated on the previous study, on which make useful from all available area to present a hole. Herein, the "standard" thin-flange Double Tee without composite topping is used where it’s commonly utilized for lightly loaded applications, such as roof structures. Each of the series of beams tested numerically and used n creating the span-service load charts, has been designated in three samples, (flange width-overall depth-with topping or without). For example; beam designated as 240-60 means that it has a flange of 2400mm and an overall depth equal to 600mm, without topping. The span-service load charts are summarized on Fig.(18) with each different case.



Retrieval Number E1921098319/2019©BEIESP
DOI: 10.35940/ijrte.E1981.098319
Journal Website: www.ijrte.org

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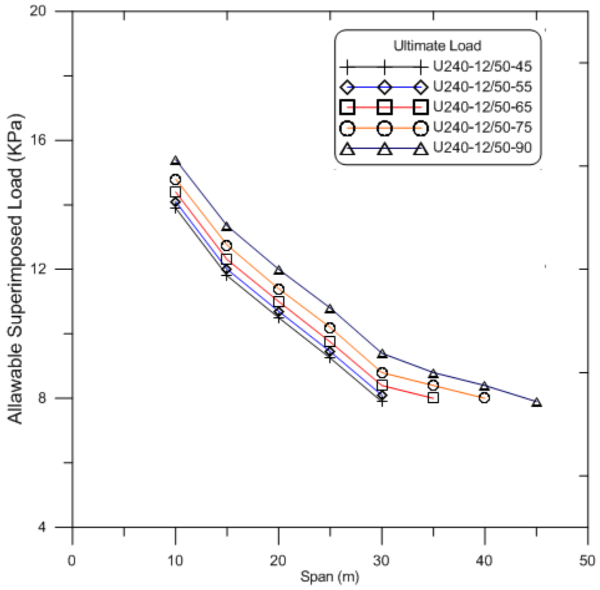
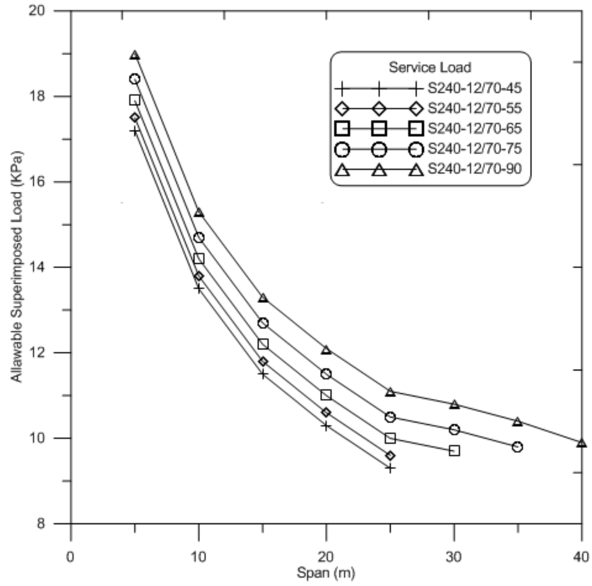

Ultimate Load
U240-12/50-45
U240-12/50-55
U240-12/50-65
U240-12/50-75
U240-12/50-90
Allawable Superimposed Load (KPa)
Span (m)


Service Load
S240-12/70-45
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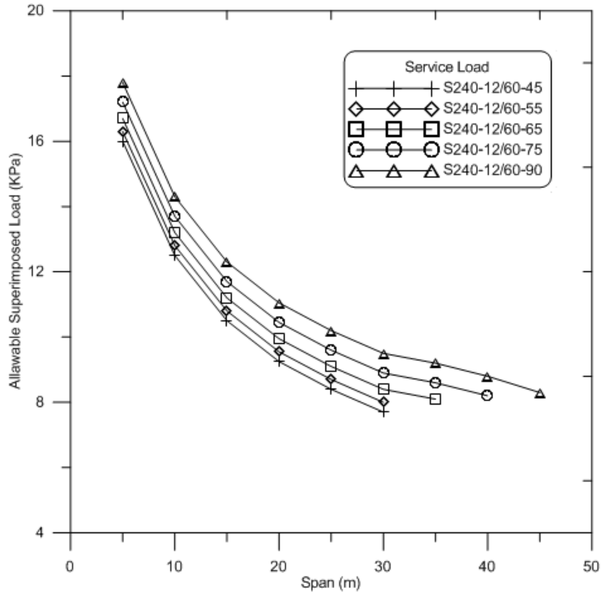
S240-12/70-90
Allawable Superimposed Load (KPa)
Span (m)


Service Load
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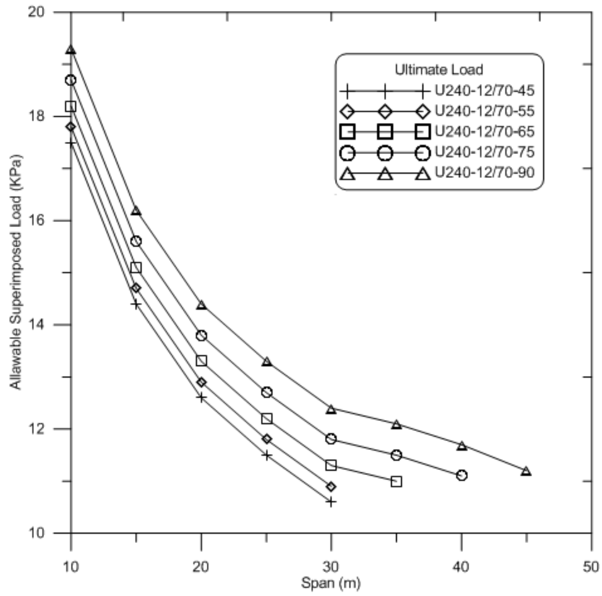
Allawable Superimposed Load (KPa)
Span (m)


Ultimate Load
U240-12/70-45
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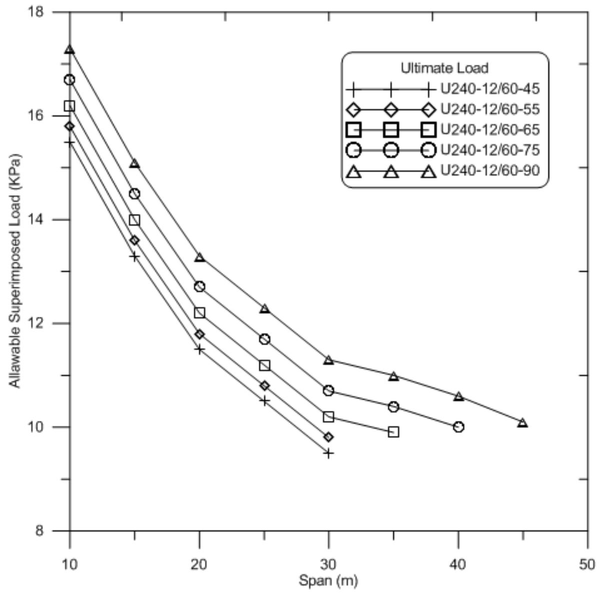
U240-12/70-90
Allawable Superimposed Load (KPa)
Span (m)


Ultimate Load
U240-12/60-45
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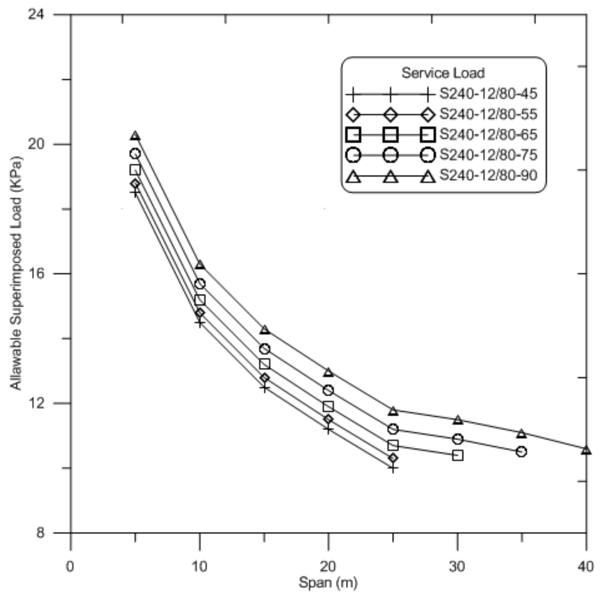
U240-12/60-75
U240-12/60-90
Allawable Superimposed Load (KPa)
Span (m)


Service Load
S240-12/80-45
S240-12/80-55
S240-12/80-65
S240-12/80-75
S240-12/80-90
Allawable Superimposed Load (KPa)
Span (m)

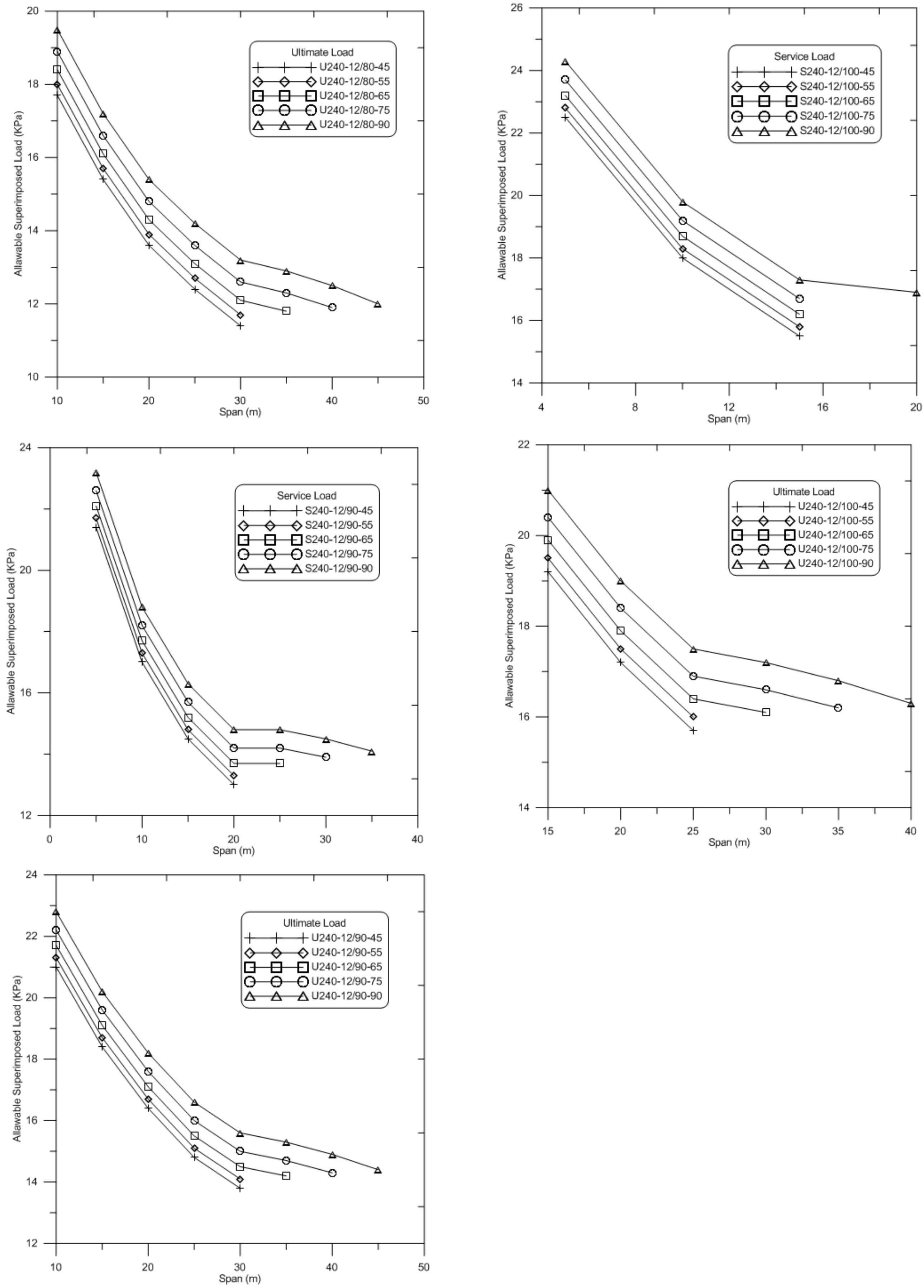


Fig. (18). Design charts for precast prestressed double tee with web openings with various compressive strength.

Note that:
The Span-Load Tables were developed in accordance with the provisions of the "Building Code Requirements for Reinforced Concrete", ACI 318-02, where in compression article[ACI 318-02, Section 18.4.2(a) [11]] was considered while in tension the article [ACI 318-02, Section 18.4.2(b) [11]] is considered.
Additional references on ([12], [13], [14], [15], [16], and [17]) where double tee beam were investigated experimentally and numerically.

VIII. CONCLUSIONS

1. This research works used a powerful tool which it is the finite element method to simulate the behavior of prestressed concrete double tee beams with web openings under flexure. The numerical tests carried out for the different cases studied showed that the predicted moment- deflection behavior and the collapse loads are in good agreement with the experimental results.
2. The influence of web opening doesn't effect that much the response of double tee beam, specially at the first stage of loading and in general the ultimate strength was closed to the control value. Also the deflection of the beams with web openings is similar to that of beams without web openings
3. Increasing concrete compressive strength improved the behavior of the prestressed double tee beam, that was appear in the plastic regain while its clearly seems that its hasn't that effect at uncracked stage of loading.
4. Higher compressive strength shows rapidly improvement, where concrete with 90MPa compressive strength jumped to 15% higher the control beam 7G1. While the moment carrying capacity does increased by about 35% within used high strength concrete for double tee beam with web opening 7G2 and 7G3, and more of that up to 65% for Beam 7G4.
5. Double tee beam with web opening 7G2 shows more ductility than other sampling beam, where that appear on its allowing for more deflection at its mid-span. About 47% more flexibility are provided by increasing the compressive strength from (48MPa - 90MPa). That response was not emerge in other beam 7G3, and 7G4.
6. In general, the beams with high strength concrete shows higher response and can developed its strength capacity much more than low strength concrete, allowing the designer to increase the span length to much more value, where that was the main goal of this research study. By adopting the finite element techniques which its being a suitable tool for large area analysis, as on creating the span-service load chart, where a large numbers of computer runs must be done. As a result; the charts could give a handy help for simple and fast design of prestressed double tee beams with web openings under flexural service load with various concrete compressive strength.

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