Analytical Investigation to Identify the Effect of Configuration of Intermediate Diaphragms on the Girders of Highly Skewed Deck Slab Bridge

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Abstract - *Bridges are the structures which are built to maintain the communication between two places which are separated by any obstacle like river, valley, road, railway in the form of crossing roadway or railway. To attend the optimum and economical solution, the bridge built on any crossing shall be perpendicular one, which results in optimized span and restrained length of pier-cap. Skew bridges are needs to be introduced in the highways or bridges to keep the alignment of roadways as straight as possible which ultimately results in smooth and speedy traffic, subsequently economy in commuting. The current investigation is carried out to analyze and study the behavior of skewed bridges and mainly to understand the effect of skewness of bridge on the intermediate diaphragms. The effect of skewness on main girders and on intermediate diaphragms studied and presented. Also, two different configurations for intermediate diaphragm are proposed and its overall behavior studied. In continuation, the effect of intermediate diaphragm on girders is studied and results were compared and presented.*

Key Words: Skewed Deck Slab Bridge, Skewness, Intermediate Diaphragms, Girders, Cross Diaphragms

1. INTRODUCTION

Skewed bridges are necessary to cross roadways, waterways or any obstacle with an angle other than 90 degrees. In general, the skewed angle is defined as the angle between the line normal to the centerline of bridge or alignment and the centerline of support (abutment or pier). The skewed angle less than 20 degrees almost stimulates almost similar behavior as that of straight bridge. But, as the angle starts increasing further, the behavior and force distribution starts changing as that of straight span. The intermediate and end diaphragms play an important part in the load distribution among the girders and the introduction of skewness in the bridge changes the load distribution completely.

The intermediate diaphragm is the member that connects two parallel running members used for resisting lateral forces resulting in transfer of loads to the points of connection. Intermediate diaphragms are a major contributor to the overall distribution of loads, particularly live loads in bridges. Almost all the bridges constructed have intermediate diaphragms, which are mostly continuous or simply supported. Continuous diaphragms provide continuity in force transfer, whereas simply supported diaphragm acts as a beam between two adjacent parallel girders. Construction of intermediate diaphragms is mostly a site activity. In steel or steel-composite bridges, they are bolted or welded with the main girders and in the case of RCC or pre-stressed bridges, they are cast integrally with the deck slab by providing appropriate reinforcement.

In the construction of skewed bridges, one of the major issues of arranging and placing the end and intermediate diaphragms, since the intermediate diaphragms are connecting at different points of the girder, there is difference in deflection of girders, which produces secondary stresses in the girders. As the skewness of bridge goes on increasing, the impact of intermediate diaphragms on girders also goes on increasing. Also, as per the configuration, the behavior and force transfer within intermediate diaphragms also changes, so as the forces in intermediate diaphragms.

As the intermediate diaphragms only distributes all the loads among the girders, it's arrangement with respect to girders plays an important role. The main objective is to analyze the skewed deck slab bridge for different configuration of intermediate diaphragm to identify the effect of intermediate diaphragms on main girders. Also, to evaluate the effect of skewness on intermediate diaphragms with different configuration as compared to straight span of the bridge. In continuation, to find the solution to minimize the effect of skewness on girders and intermediate diaphragms, so that optimum design can be presented.

2. REVIEW OF LITERATURE

Till now multiple studies are carried out on the analysis of skewed desk slab bridges and load distribution factors in skewed bridges. Few literatures are also available on how intermediate diaphragms contribute in overall behavior of deck slab bridges. Ali Khaloo and Mirzabozorg (2003) [7] analyzed simply supported bridges consisting of five I-section concrete girders by finite element method and carried out the parametric study to workout the load distribution factors. Oguz C. Celik & Michel Bruneau (2011) [4] addressed the issue of implementing the ductile diaphragms in skewed bridges which are introduced by the AASHTO guide specifications as a structural system that can be used to resist transverse earthquake effects. It was observed that, the base shear strength and lateral stiffness of end diaphragm decreases & drift increases as the skew angle increases. Jawad Gull, Atorod Azizinamini & Todd Helwig (2017) [2] worked on the structural responses provided by the different detailing methods for the skewed steel I girder bridges along with intermediate diaphragms. Jennifer McConnell, Matija Radovic & Kelly Ambrose (2016) [3] carried out the field test to understand the relationship among girder stresses, cross-frame design and skew angle of two steel I-girder bridges, which have moderate and high levels of skew and differing cross-frame designs. Walter Dilger, Gamal Ghoneim & Gamil Tadros (1988) [10] carried out the study to identify the effect of diaphragms on the reactions, internal forces, and behavior of skew box girder bridges for skew diaphragms, orthogonal diaphragms and no diaphragms condition.

3. MATERIALS AND METHODS

In the current study, a typical 50m deck slab bridge with skewed angle of 60 degrees was considered for the analytical investigation. Table 1 shows the properties of material which are used in the analysis. Table 2 and 3 shows the sectional properties of members and dimensional parameters of geometry, respectively.

Table -1: Material Properties

Grade of Material	Density of Material
Concrete Grade M50 Reinforcement Steel Grade FE500 Structural Steel Grade E350	Concrete Density = 25 KN/m³ Steel Density = 77 KN/m³

Table -2: Sectional Properties of Members

Main Girder Properties		Intermediate Diaphragm Properties: "X bracing is used"		End Diaphragm Properties	
Top Flange:	700mm x 32mm	Top chord:	2 ISA-150x150x10	Top Flange:	500mm x 20mm
Bottom Flange:	900mm x 40mm	Bottom chord:	2 ISA-150x150x10	Bottom Flange:	600mm x 25mm
Web:	2650mm x 25mm	Inclined chords:	2 ISA-150x150x10	Web:	2000mm x 16mm
Overall Height:	2722mm			Overall Height:	2045mm

Table -3: Dimensional Parameters of Geometry

Component of Bridge Section	Dimension (Length/Width/Depth)
Width of Each Carriageway	7.50m (2 Lanes)
Width of Median	1.20m
Width of Anti-Crash Barrier	0.50m
Overall Carriageway Width	7.50 x 2 + 1.20 + 0.50 x 2 = 17.20m
C/c spacing between the girders	2.80m (typical)
Cantilever span at both ends	1.60m (transversely)
Thickness of Deck-Slab	0.25m
Thickness of wearing coat	0.09m
Drainage slope	2.50%

The actual cross-section of bridge is shown in Fig. 1 whereas, Fig. 2, 4 and 5 shows the line diagram of bridge model in plan. For the analysis purpose, Midas Civil software is used. For comparison and initial understanding of forces and behavior, a standard 50m straight model (with skew angle 0 degrees) is prepared and plan view of the same is shown in Fig. 2.

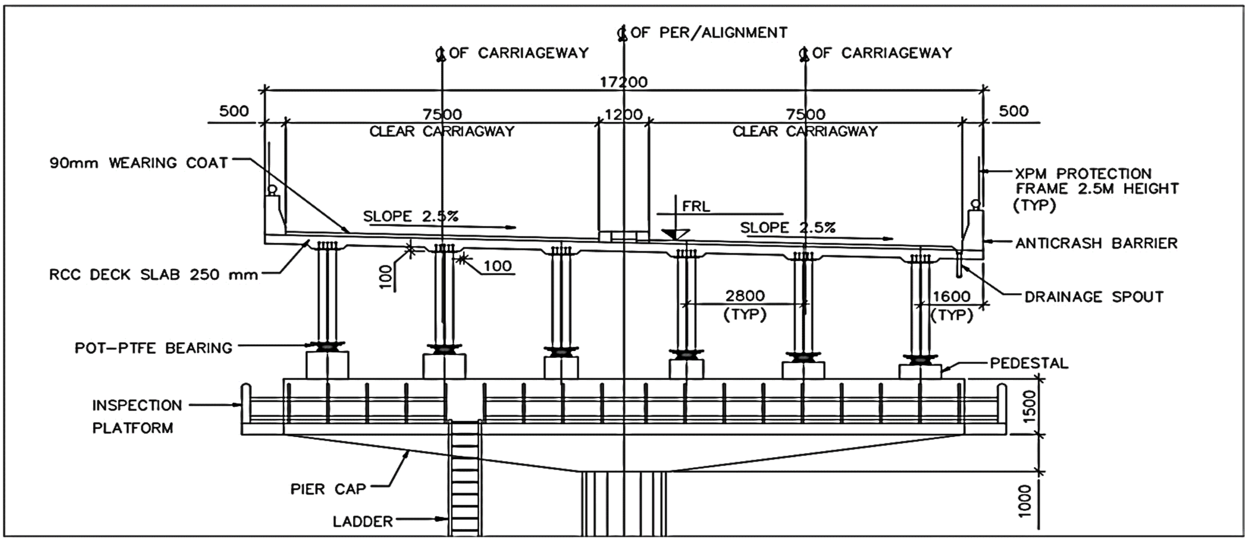

Fig -1: Cross-section of Bridge

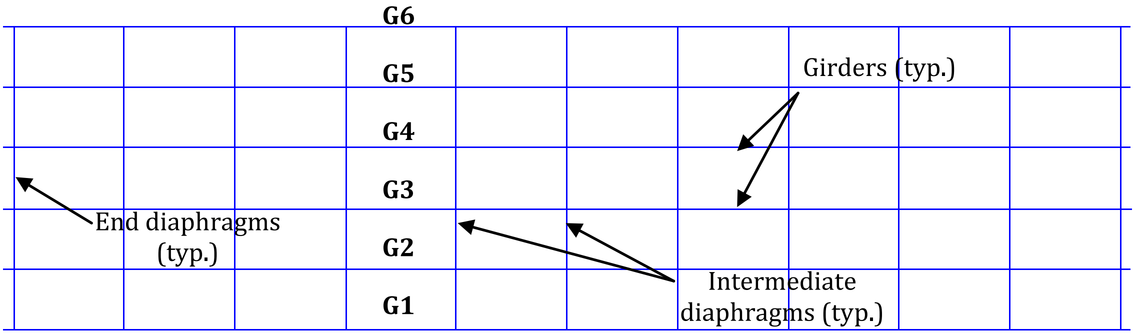

Fig -2: Plan of 50m Straight Bridge Span

The intermediate diaphragm arrangement is shown in Fig. 3. They are connected to two adjacent girders with bolting arrangement and are at different elevations to maintain the transverse slope of drainage in one direction.

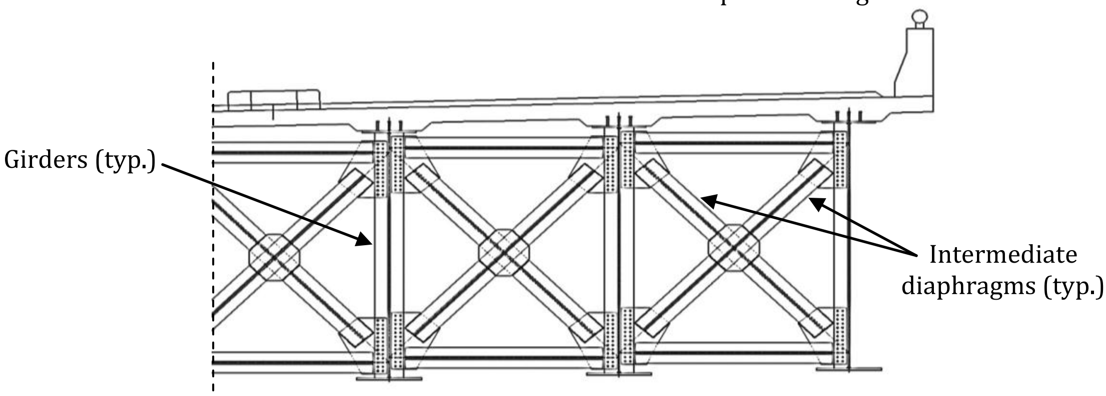

Fig -3: Sketch Showing Arrangement of Intermediate Diaphragms

Two different configurations of intermediate diaphragms are proposed to fulfill the prime objective of the research. Fig. 4 and Fig. 5 shows plan view of the skewed bridge span with two different arrangements of intermediate diaphragms. These models are further used for force comparison and interpretation of results.

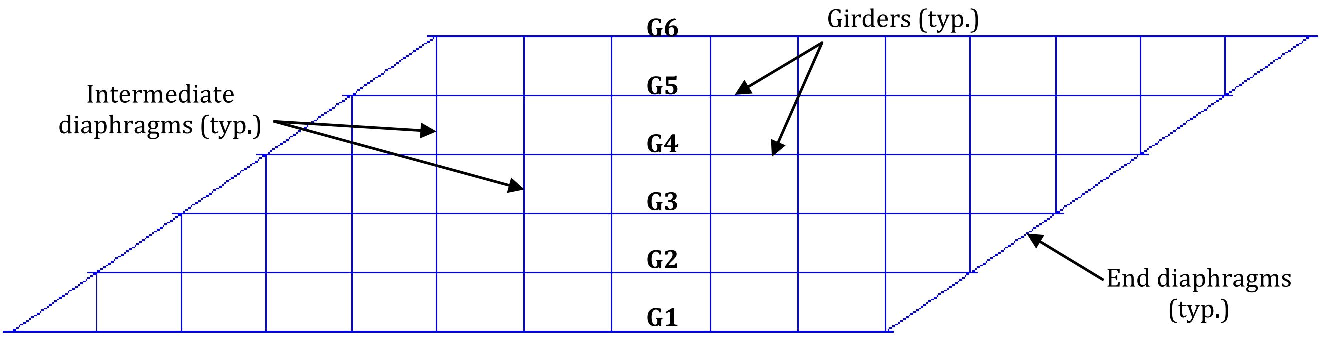

Fig -4: Configuration 1 of Intermediate Diaphragm for Skewed Span

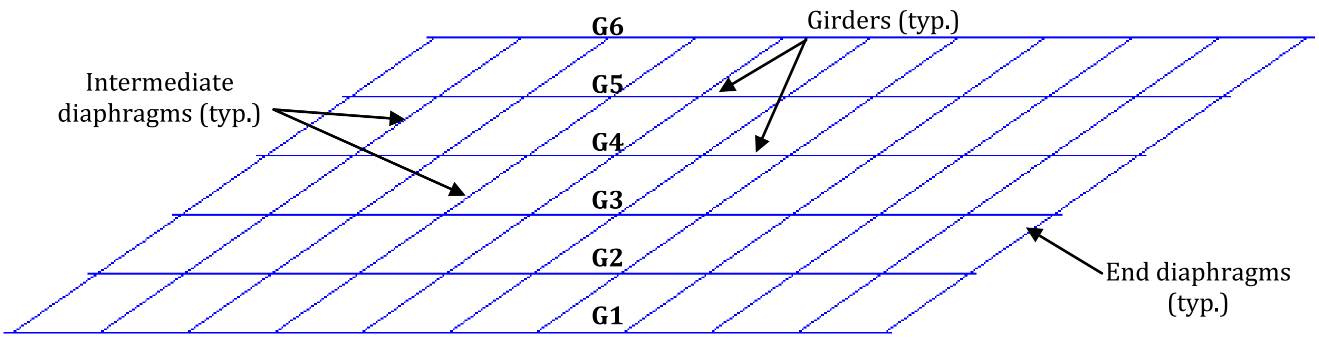

Fig -5: Configuration 2 of Intermediate Diaphragm for Skewed Span

4. LOADING DETAILS

The typical set of loadings considered is as follows:

[1] Self-weight of the girders:
The self-weight of girders is considered with the help of "SELF-WEIGHT" command of the software. Factor of 1.20 is considered to account the other miscellaneous fixtures/ loads.

[2] Deck Slab:
250mm thk. deck slab with density of concrete as 25 kN/m^3
Area load = 0.25 x 25 = 6.25 kN/m^2

[3] Wearing Coat:
90mm thk. wearing coat with density as 22 kN/m^3
Area load = 0.09 x 22 = 1.98 kN/m^2

[4] Crash Barrier:
Area of CB is approximately around 0.50 m^2 with density as 25 kN/m^3
Uniform load = 0.50 x 25 = 12.50 kN/m
This uniformly distributed load applied on the peripheral girders of the system.

[5] Median:
Median is approximately 0.50 m in depth and 1.20m wide with density as 25 kN/m^3
Area load = 0.50 x 25 = 12.50 kN/m^2
This uniformly distributed load applied on the central two girders of the system.

[6] Live Loads:
Live loads are considered as per code IRC:6-2017 (Standard Specifications and Code of Practice For Road Bridges). Importantly, vehicles Class A and Class 70R (wheeled) are considered for the live load combinations.
Live load combinations primarily are single Class A vehicle, two Class A vehicle and single Class 70R vehicle in each lane. For the analysis of both the lanes, combination of vehicles in each lane are considered and critical or noteworthy load combination is identified for the force extraction and further comparison.

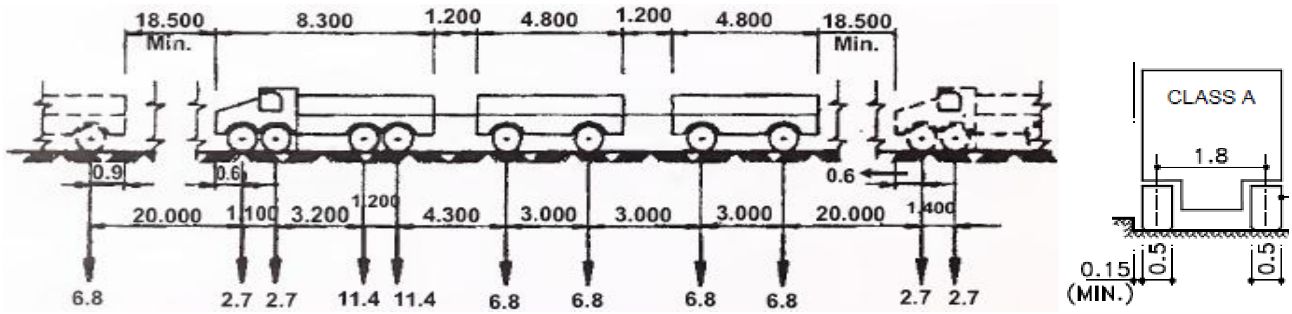

Fig -6: Class A Train of Vehicles
(Load values are in 'Ton' & Dimensions are in 'm')

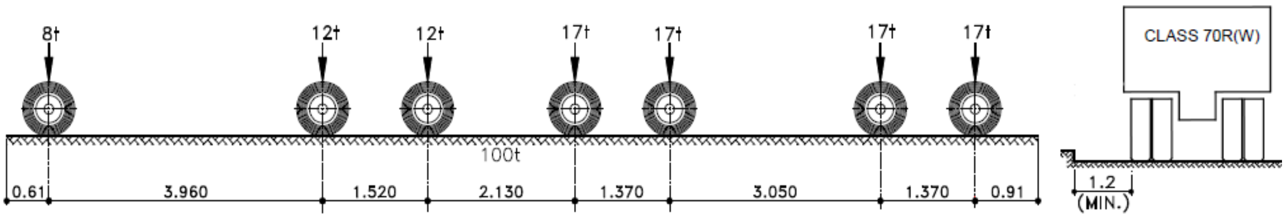

Fig -7: Class 70R Train of Vehicles
(Load values are in 'Ton' & Dimensions are in 'm')

4.1 Boundary Conditions

The boundary or supports are the one, where generally girder rests on the pier-cap or abutment. Often supports are in the form of different type of bearing like elastomeric bearing, POT-PTFE bearing, neoprene bearing and so on. These bearings provide translational or rotational movement depending on the design requirements and it also affects the overall behavior of the structure, specially the sub-structure.

The boundary conditions for the girders are considered as shown in fig. 8. It shows for the 50m straight span and same conditions are further used for skewed span also for both the configurations with 60 degrees skewed angle.

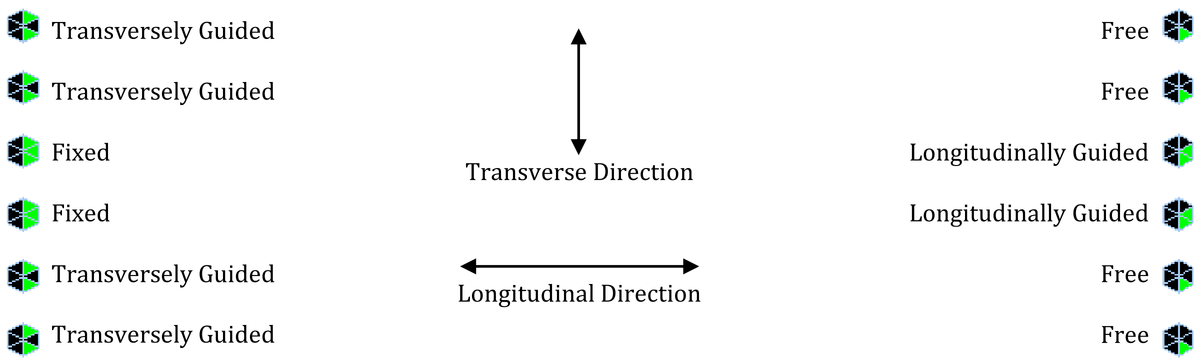

Fig -8: Plan Showing Boundary Conditions Considered For The Girders

5. RESULTS AND DISCUSSION

Following are the graphs of bending moment diagrams plotted for the girders G1 to G6 for various load cases with straight span, intermediate diaphragm configuration 1 and intermediate diaphragm configuration 2.

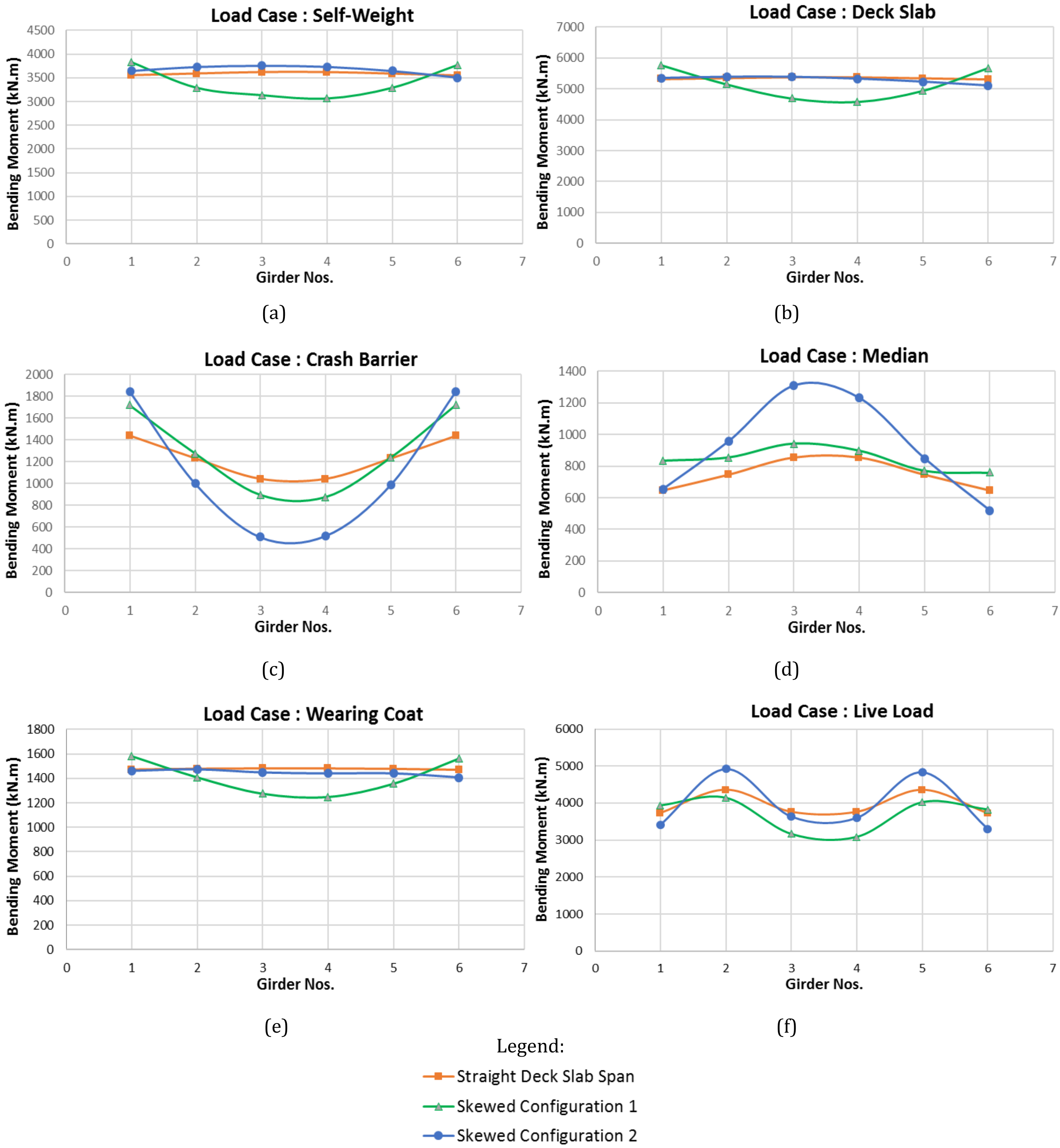

Chart -1: Bending Moment Diagrams for Various Load Cases (kN.m)

Following are the graphs of shear force diagrams plotted for the girders G1 to G6 for various load cases with straight span, intermediate diaphragm configuration 1 and intermediate diaphragm configuration 2.

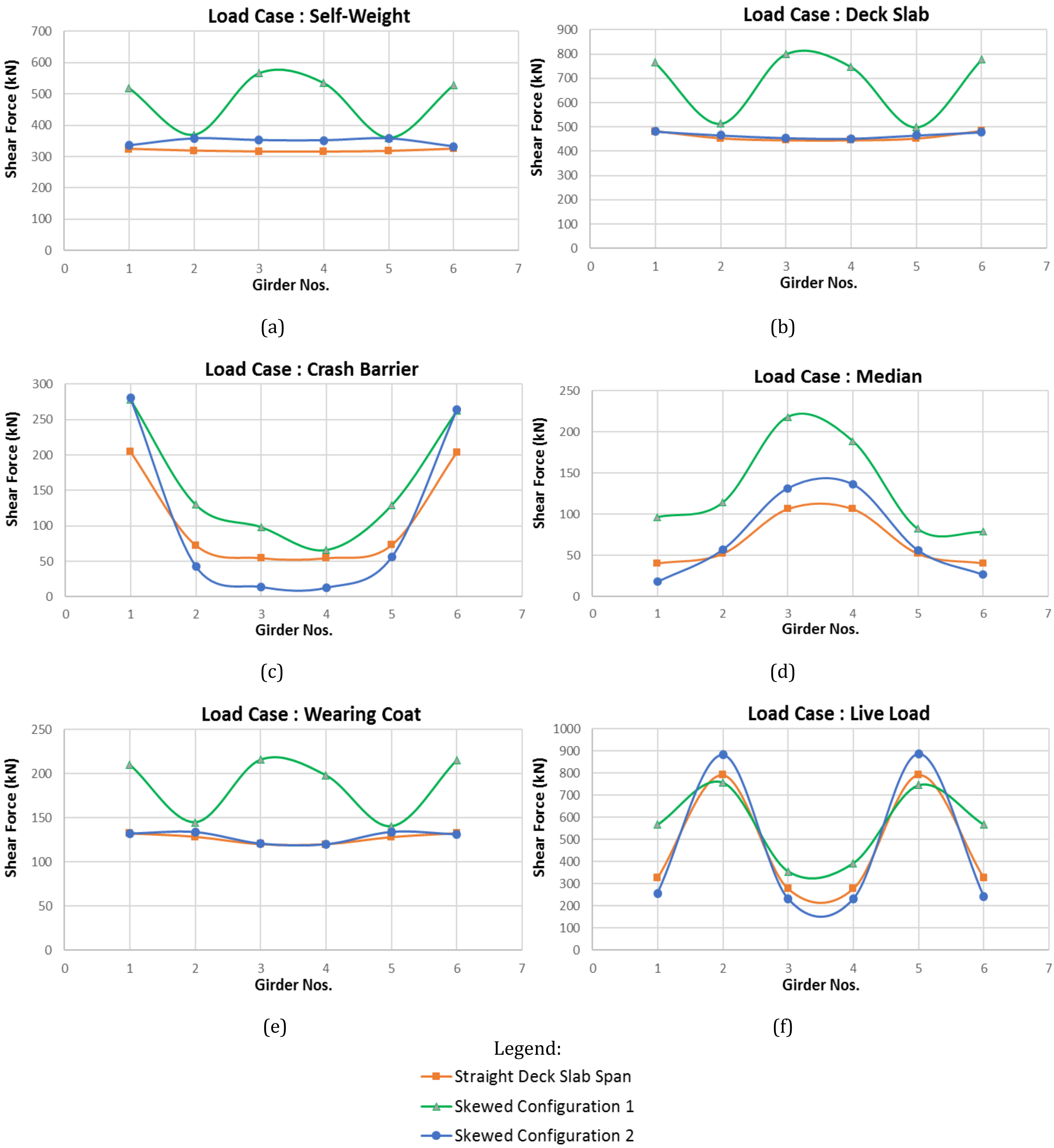

Chart -2: Shear Force Diagrams for Various Load Cases (kN)

Following is the chart showing comparison of axial forces developed in the intermediate diaphragms for various load cases with straight span, intermediate diaphragm configuration 1 and intermediate diaphragm configuration 2.

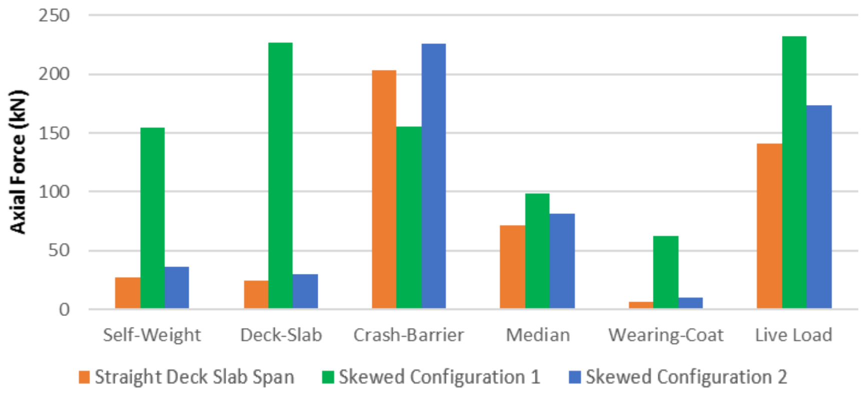

Chart -3: Comparison of Axial Forces Developed In Intermediate Diaphragms

5.1 Discussion of the results

The straight model of span 50m is prepared with loadings as mentioned in section 4. In continuation, respective skewed models are prepared with 60 degrees of skewness. Two different configurations for intermediate diaphragms are proposed and the force comparison is done and presented for the girders and intermediate diaphragms in section 5.0.

The comparison of bending moments generated in girders G1 to G6 for straight span, 1st skewed and 2nd skewed configuration is plotted in Chart-1 for individual load cases. From these comparative graphs, it can be observed that,

a. For the load case *Self-Weight*, the bending moment values obtained for straight span and with 2nd skewed configuration are almost identical in behavior and same in values. There is a significant difference in values and behavior of bending moments obtained with 1st skewed configuration. The bending moment values are in the range of 3520 kN.m to 3750 kN.m for straight span and 2nd skewed configuration, while variation of bending moment is more for 1st skewed configuration ranging from 3000 kN.m to 3750 kN.m.

b. For the load case *Deck Slab*, the values of bending moments are different as that of load case Self-Weight but, the behavior of results are in line i.e. results of straight span and the one obtained with 2nd skewed configuration are same. The bending moment values are in the range of 5500 kN.m for straight span and 2nd skewed configuration, while variation of bending moment is more for 1st skewed configuration ranging from 4500 kN.m to 5750 kN.m.

c. For the load case *Crash Barrier*, the peripheral two girders get more influenced, as the location crash barrier is at the edges. These girders majorly considered for the comparison. It can be seen that, all the three conditions behave differently under this loading and gives different behavior. The bending moment generated for straight span is around 1400 kN.m, for 1st skewed configuration is around 1700 kN.m whereas for 2nd configuration it is around 1850 kN.m.

d. For the load case *Median*, the central two girders get more influenced, as the location of median is at the center of the bridge. These girders majorly considered for the comparison. It can be seen that, all the three conditions behave differently under this loading and gives different behavior. The bending moment generated for straight span is around 850 kN.m, for 1st skewed configuration is 950 kN.m whereas for 2nd configuration it is around 1300 kN.m.

e. For the load case *Wearing Coat*, the values of bending moments are different as that of load case Deck Slab but, the behavior of results are in line i.e. results of straight span and the one obtained with 2nd skewed configuration are same. The bending moment values are in the range of 1400 kN.m to 1500 kN.m for straight span and 2nd skewed configuration, while variation of bending moment is more for 1st skewed configuration ranging from 1250 kN.m to 1600 kN.m.

f. For the load case *Live Load*, the combination of vehicle 70R in each lane is critical and shows the appropriate results. The bending moment generated for straight span is around 3750 kN.m to 4500 kN.m and for 1st skewed configuration it is 3000 kN.m to 4000 kN.m whereas for 2nd configuration it is around 3500 kN.m to 5000 kN.m. Though results are not similar with each other, behavior is identical in all the cases and the point to be noted here is that, the variation in values of bending moment is much higher in the case of 2nd skewed configuration.

Following to the comparison of bending moment, maximum shear forces, in other words, reaction values generated in girders G1 to G6 for straight span, 1st skewed and 2nd skewed configuration is plotted in Chart-2 for individual load cases. From these comparative graphs, it can be observed that,

a. For the load case *Self-Weight*, the shear force values obtained for straight span and with 2nd skewed configuration are almost identical in behavior. There is a significant difference in values and behavior of shear forces obtained with 1st skewed configuration. The shear force values are in the range of 320 kN to 360 kN for straight span and 2nd skewed configuration, while variation of shear force is more for 1st skewed configuration ranging from 360 kN to 550 kN.

b. For the load case *Deck Slab*, the values of shear forces are different as that of load case Self-Weight but, the behavior of results are in line i.e. results of straight span and the one obtained with 2nd skewed configuration are same. The shear force values are in the range of 450 kN to 475 kN for straight span and 2nd skewed configuration, while variation of shear force is more for 1st skewed configuration ranging from 500 kN to 800 kN.

c. For the load case *Crash Barrier*, the peripheral two girders get more influenced, as the location crash barrier is at the edges. These girders majorly considered for the comparison. They behave differently under the three conditions and gives different behavior. The shear force generated for straight span is around 210 kN, for 1st skewed configuration is around 270 kN whereas for 2nd configuration it is around 275 kN.

d. For the load case *Median*, the central two girders get more influenced, as the location of median is at the center of the bridge. These girders majorly considered for the comparison. They behave differently under the three conditions and gives different behavior. The shear force generated for straight span is around 120 kN, for 1st skewed configuration is 200 kN whereas for 2nd configuration it is around 130 kN.

e. For the load case *Wearing Coat*, the value of shear forces is different as that of load case Deck Slab but, the behavior of results is in line i.e. results of straight span and the one obtained with 2nd skewed configuration are same. The shear force values are in the range of 120 kN to 140 kN for straight span and 2nd skewed configuration, while variation of shear force is more for 1st skewed configuration ranging from 140 kN to 220 kN.

f. For the load case *Live Load*, the combination of vehicle 70R in each lane is critical and shows the appropriate results. The shear force generated for straight span is around 300 kN to 800 kN and for 1st skewed configuration it is 350 kN to 750 kN whereas for 2nd configuration it is around 220 kN to 900 kN. Though results are not similar with each other, behavior is identical in all the cases and the point to be noted here is that, the variation in values of bending moment is much higher in the case of 2nd skewed configuration as compared with other two.

Comparison of axial forces for Intermediate Diaphragms

As we have seen, how different configurations of intermediate diaphragm impacts the overall behavior of girder and variation in design forces like bending moments, shear forces, etc., the intermediate diaphragm also behaves differently under different configurations. As the intermediate diaphragms are primarily axial force carrying members, the axial forces developed under all the 3 conditions are plotted in Chart-3 for individual load cases. It can be seen that,

a. For the load case *Self-Weight*, the axial forces developed in intermediate diaphragms are identical in straight span and 2nd skewed configuration and are around 25 kN to 30 kN. 1st configuration gives very much high value around 155 kN.

b. For the load case *Deck Slab*, the axial forces developed in intermediate diaphragms are identical in straight span and 2nd skewed configuration and are around 25 kN to 30 kN. 1st configuration gives very much high value around 225 kN.

c. For the load case *Crash Barrier*, the axial forces developed in intermediate diaphragms are identical in straight span and 2nd skewed configuration and are around 200 kN to 225 kN. 1st configuration gives comparatively low value around 150 kN.

d. For the load case *Median*, the axial forces developed in intermediate diaphragm are almost identical under all the 3 conditions and value varies from 75 kN to 100 kN.

e. For the load case *Wearing Coat*, the axial forces developed in intermediate diaphragms are identical in straight span and 2nd skewed configuration and are around 10 kN. 1st configuration gives comparatively high value of 60 kN as compared with other two.

f. For the load case *Live Load*, the combination of vehicle 70R in each lane is critical and shows the appropriate results. The axial force for straight span is around 140 kN and for 1st skewed configuration, it is 235 kN whereas for 2nd configuration it is around 175 kN. The point to be noted here is that, the value of axial force is much higher in the case of 1st skewed configuration as compared with other two.

6. CONCLUSIONS

A 50m straight span grillage model was prepared and 60 degrees skewed model with two different intermediate configurations were prepared. These are then analyzed and major design forces like bending moments, shear forces are compared and plotted for 6 different load cases. The behavior pattern of girders with respect to these proposed 2 different configurations of intermediate diaphragms were studied. Also, the axial forces in intermediate diaphragm are observed and compared. Following conclusions are made from the observations.

1. The 1st skewed configuration results in uneven distribution of forces and gives reduced economy in the girders. There is more difference in design values when it is compared with standard straight span condition. The reason for this is, in this configuration, the intermediate diaphragm connects the two dissimilar deflection point of girders. But, the construction with this configuration is easy and more feasible.

2. The 2nd skewed configuration results in even distribution of forces and most optimized design of the girders. The value of design forces and behavior of girders are almost in line with the standard straight span condition. The reason for this is, in this configuration, the intermediate diaphragm connects the two similar deflection point of girders, very similar with straight span condition. But, the construction with this configuration is difficult and more time consuming.

3. It can be concluded that, the configuration of intermediate diaphragms plays an important role in distribution of forces and it majorly control the design forces developed in the girders. The proper selection of configuration of intermediate diaphragms can lead to even distribution of forces, resulting in optimized design of girders.

4. The axial forces generating in the intermediate diaphragm can also be controlled by choosing the proper configuration. While 1st skewed configuration attracts more forces, 2nd skewed configuration gives almost same results as that of straight span.

5. The proper pre-cambering is also the solution to reduce the differential deflection of girders at the two diaphragm connecting points, which can also lead to proper distribution of forces. Camber shall be provided for all the load cases except live load to achieve the full advantage. This will work by generation of less axial forces in diaphragm, as it is happening in the case of straight or 2nd skewed configuration.

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