4th International Conference on Advances in Civil Engineering 2018 (ICACE 2018)
19 –21 December 2018
CUET, Chittagong, Bangladesh
www.cuet.ac.bd

COMPARISON OF FORCE-BASED DESIGN AND DISPLACEMENT-BASED DESIGN METHODS FOR SEISMIC RESPONSE OF MULTISPAN BRIDGES

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ABSTRACT

Multispan bridges are very common structures in transportation system. Generally, all the bridges are designed using force-based design (FBD) method. Though displacement correlates damage better than strength does, FBD assumes damage in the structure is controlled by the provision of strength and uses displacement as the final check to determine the structural performance. Although current FBD method is considerably improved, there are some fundamental problems in its procedure. Displacement-based design (DBD) methods have been developed overcoming deficiency associated with FBD method. In this study, two DBD methods, direct displacement-based design (DDBD) and alternative displacement-based design (ADBD), have been compared with FBD method for the seismic response of multispan bridges. Two different configurations of bridge models are considered here to compare their seismic response. Base shear and displacement are taken as primary seismic response parameter for this study. From the numerical evaluation it can be concluded that, DBD methods have shown better performance in calculating seismic responses than FBD method. Base shear calculated by DDBD and ADBD methods are less than that calculated by FBD method, whereas displacement estimated by DDBD and ADBD methods are more than that estimated by FBD method.

Keywords: multispan bridge; force-based design; direct displacement-based design; alternative displacement-based design; seismic response.

INTRODUCTION

Bridges are very important structures for safe and smooth passage of vehicles over rivers, roads, railways and other features. Bridges also connect islands to mainland (Bhuiyan and Alam 2012, Bhuiyan and Alim 2017). Since bridges are one of the most critical components of highway systems, it is necessary to evaluate the seismic safety of highway bridges in terms of seismic response (Hwang et al., 2001). Multi-span bridges are generally used when width of the obstacle is large. These bridges can be simply supported or continuous. Continuous bridges are more economical because less thickness can be provided due to less bending moment in midspan. They are suitable where there is no possibility of uneven settlement of foundations. But analysis of continuous bridges is more complex and they need more detailing (Chen and Duan, 2000). Bridges can be considered as simple structures as they possess little number of elements. At the same time this simplicity makes bridge structure less redundant. Failure of one element or connection between elements can cause collapse due to lack of alternate load path (Ghosn and Yang, 2014). Any kind of damage of bridges will destroy the transportation system. So, special care should be given in designing bridges.

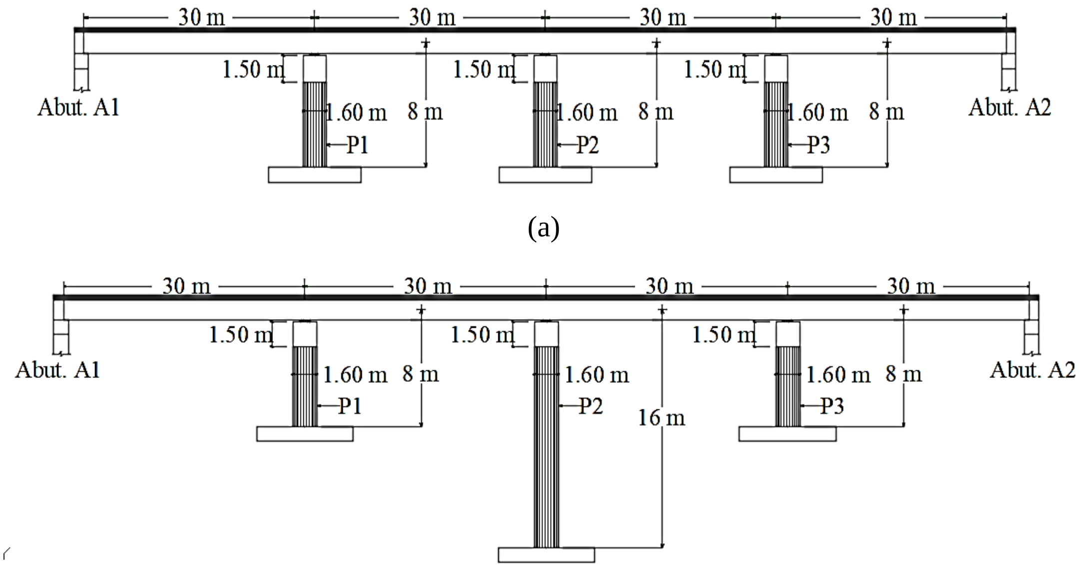
On the basis of above background, the study aims to evaluate analytically the seismic response of multispan bridges of two different configurations based on the variation of pier height to compare the estimation of seismic response by force-based Design (FBD) method with those by direct displacement-based design (DDBD) and alternative displacement-based design (ADBD) method. Base shear and displacement are taken as seismic response parameter for this study. Design response spectrum of Bangladesh National Building Code (BNBC Final draft, 2015) is used for the analysis in this study. Finally, these three methods have been compared for evaluating base shear and displacement in both of the longitudinal and transverse direction.

MODELING OF MULTISPAN BRIDGES

Multispan continuous bridges of two different configurations shown in Fig.1 are taken into consideration for this study with the variation of pier height. The geometric dimensions of pier-girder system are shown in Fig. 2. Each configuration of bridge models consists of spans with 30 m length. Bridge model 1 shown in Fig. 1(a) consists of three piers with equal height of 8 m whereas; Fig. 1(b) shows bridge model 2 with two equal outer piers of 8 m with a central pier of 16 m height. The diameter of each circular pier is taken as 1.60 m for both models (Fig. 1 and Fig. 2). Both of the bridge models also consist of similar span width of 12 m (Fig. 2). The layout of the superstructure is straight and continuous over the pier cap of size 1.6 m × 1.5 m for both models (Fig. 1 and Fig. 2). A hollow continuous box girder is considered for the deck of the bridge models (Fig. 2). Connection between pier top and box girder is considered as pinned. The superstructure is free to move both in the longitudinal and transverse direction. Pier longitudinal and transverse reinforcements are calculated for the critical case and used for all other cases. In addition to dead load, an area load of 1.7 kN/m^2 is taken in consideration for wearing surface. The bridge models are considered to be situated in a region with PGA value of 0.28g (BNBC Final draft, 2015). Site class is taken as B and importance category of the bridge is taken as critical and response reduction factor is taken as 1.5 (AASHTO, 2006). Both bridge models are analytically modelled in CSI Bridge software and analyzed by FBD, DDBD and ADBD method. Reinforcement details and material properties of piers for all models are described in Table 1.

Table 1: Pier reinforcement and material properties

Clear cover to longitudinal reinforcement	50 mm
Percentage of longitudinal reinforcement, ρ_l (92 nos., d_b= 32 mm)	3.74 %
Strain to ultimate stress of longitudinal reinforcement	0.10
Percentage of transverse reinforcement, ρ_t (d_b= 16 mm, s = 90 mm)	0.59 %
Strain to ultimate stress of transverse reinforcement	0.12
Concrete compressive strength, f_c'	27.5 MPa
Reinforcement yield strength, f_y	414 MPa



(a)

(b)

Fig. 1: Four span bridge models; (a) Model 1- bridge with equal pier heights (b) Model 2- bridge with unequal pier heights (high central pier)

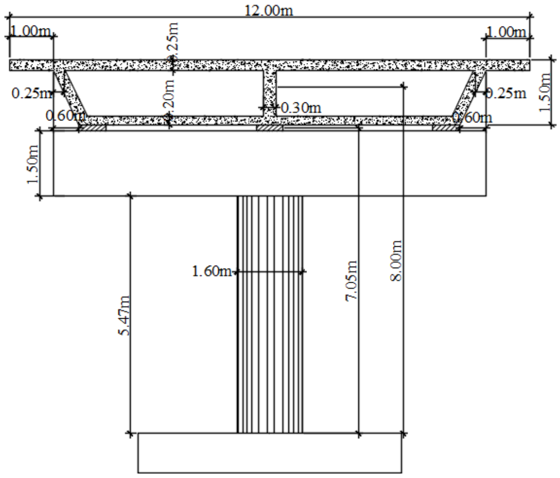


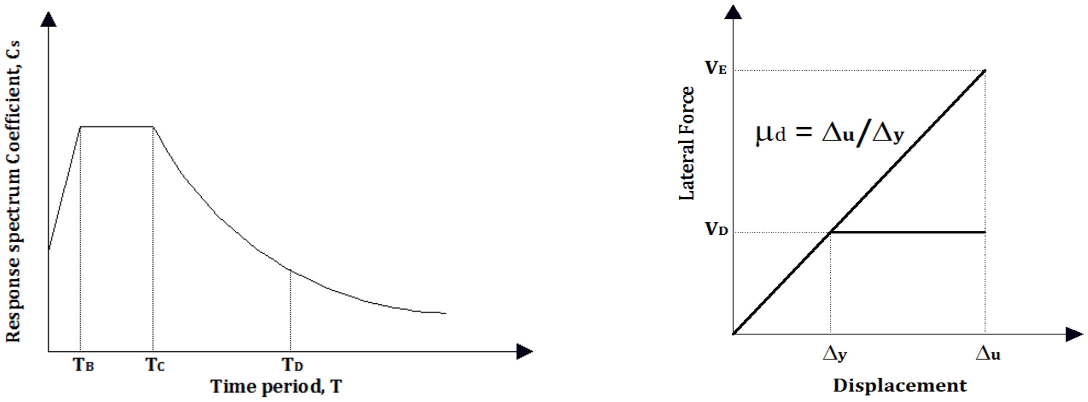
Fig. 2: Geometric dimensions of pier-girder system

METHODOLOGY

Different approaches have been developed to accomplish seismic design of bridges. FBD and DBD methods are considered for the seismic response analysis of multispan bridges in this study.

Force-Based Seismic Design

In force-based design (FBD) method forces are calculated corresponding to elastic response to a design acceleration response spectrum. In this process, elastic stiffness is used. These elastic forces are then divided by a response-reduction factor representing the assessed displacement ductility capacity. The structure is then designed for these reduced forces, and the displacement is checked with code-specified limits. If displacement does not meet the requirement, the process is repeated. The main philosophy of FBD is shown in Fig. 3, where T_B, T_C, T_D are characteristic time periods of design response spectrum as a function of site class. The bridge models (Fig. 1) are analyzed by FBD method in this study to compare the seismic response of bridges with DBD methods.



(a) (b)

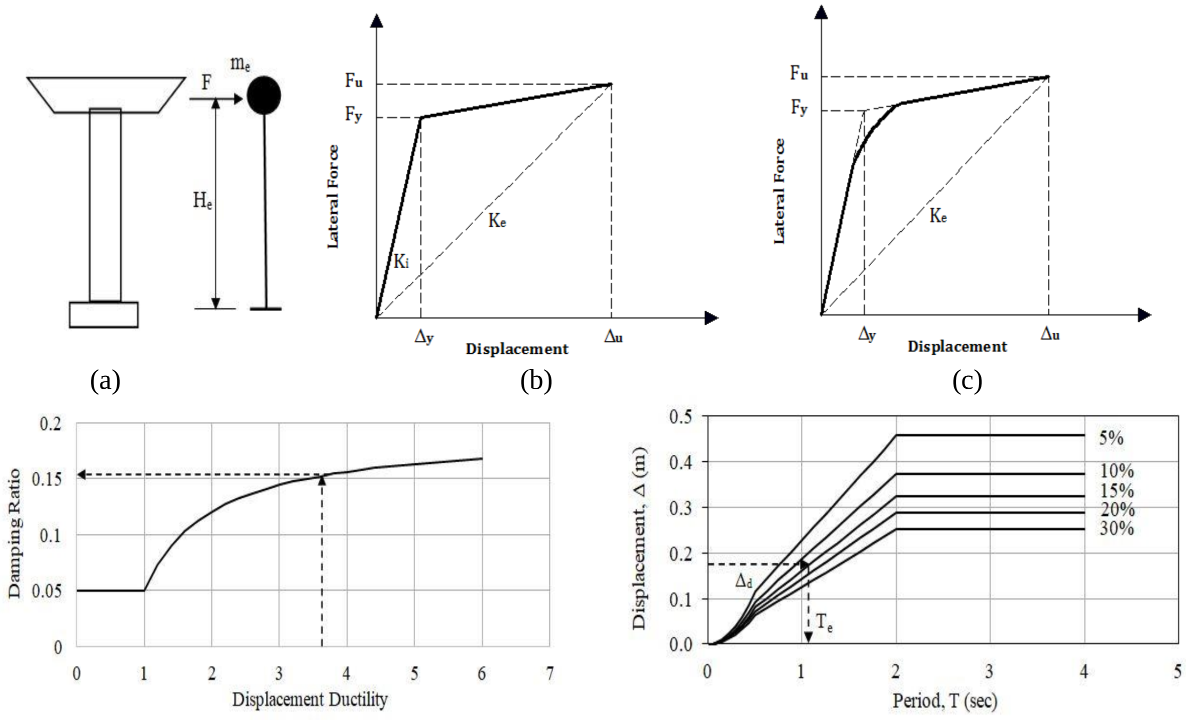
Fig. 3: FBD method; (a) typical design acceleration response spectrum (b) reduction of elastic force

Displacement-Based Seismic Design

A number of new methods have been developed overcoming deficiency associated with FBD method, direct displacement-based design (DDBD) and alternative displacement-based design (ADBD) method are among them. DDBD method, first proposed by Priestley (1993), aims at obtaining a structure, which will reach a target displacement profile when subjected to earthquakes consistent with a given reference response spectrum. The performance levels of the structure are governed through the selection of suitable values of the maximum displacement and maximum drift. After calculating yield displacements from the geometry of the elements, displacement ductility demands may be directly calculated from target displacements (Δ_d). Starting with this ductility and with a set of response displacement spectra, the effective period (T_e) of an equivalent linear SDOF system is determined at peak displacement, considering an equivalent damping ratio (ξ_e). The effective stiffness (K_e) of the equivalent SDOF system at maximum displacement can be found from Eq. (1) using effective mass (m_e) of the structure participating in the fundamental mode of vibration. Finally, design base shear force, is calculated by Eq. (2).

$$K_e = 4\pi^2 \frac{m_e}{T_e^2} \quad (1)$$

$$F = V_{base} = K_e\Delta_d \quad (2)$$



(a) (b) (c)

(d) (e)

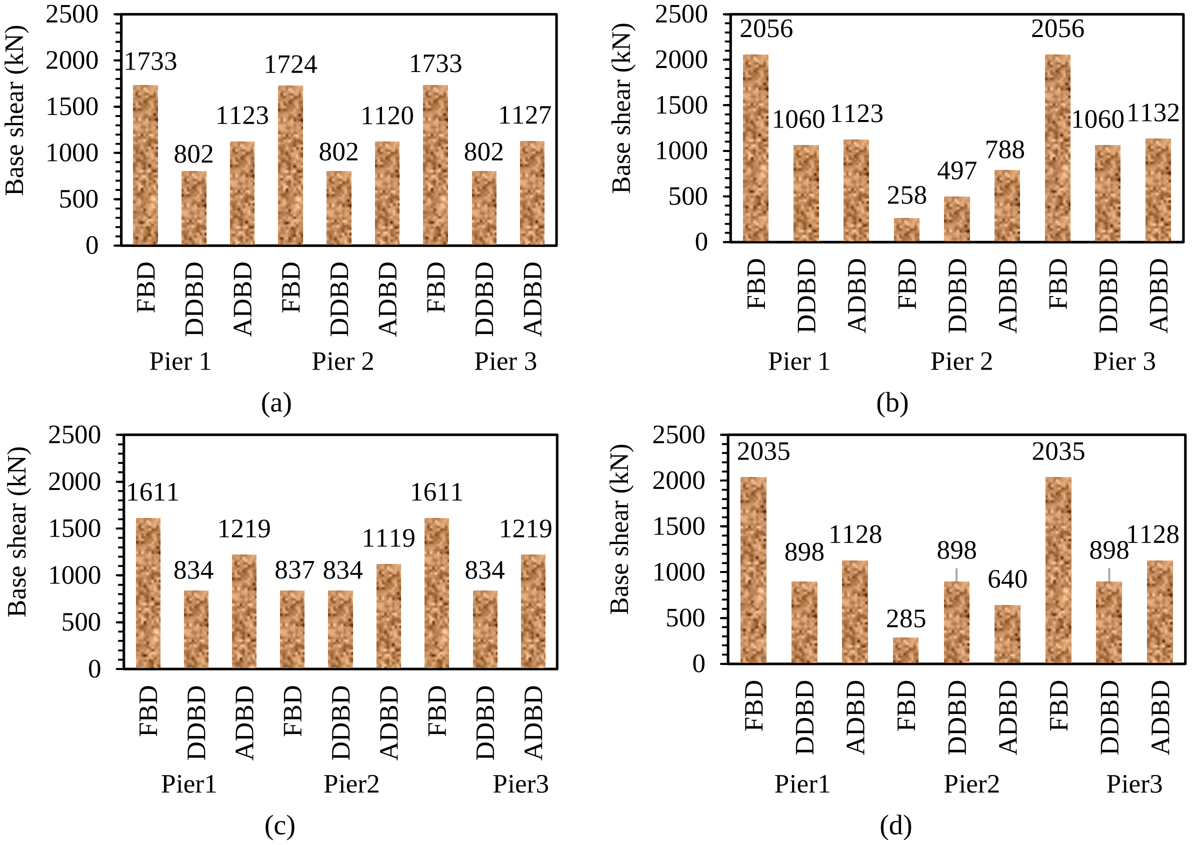
Fig.4: DBD methods; (a) SDOF simulation (b) effective stiffness for DDBD (c) effective stiffness for ADBD (d) Effective damping ratio estimation (e) effective period estimation from displacement spectra

The only difference between DDBD and ADBD is that, ADBD utilizes pushover analysis to determine yield displacement (Δ_y), ultimate displacement (Δ_u) and ultimate force (F_u), from which effective stiffness is calculated. The main philosophy of DBD methods are shown in Fig. 4. The bridge models (Fig. 1) are also analyzed by DDBD and ADBD methods in this study.

NUMERICAL RESULTS

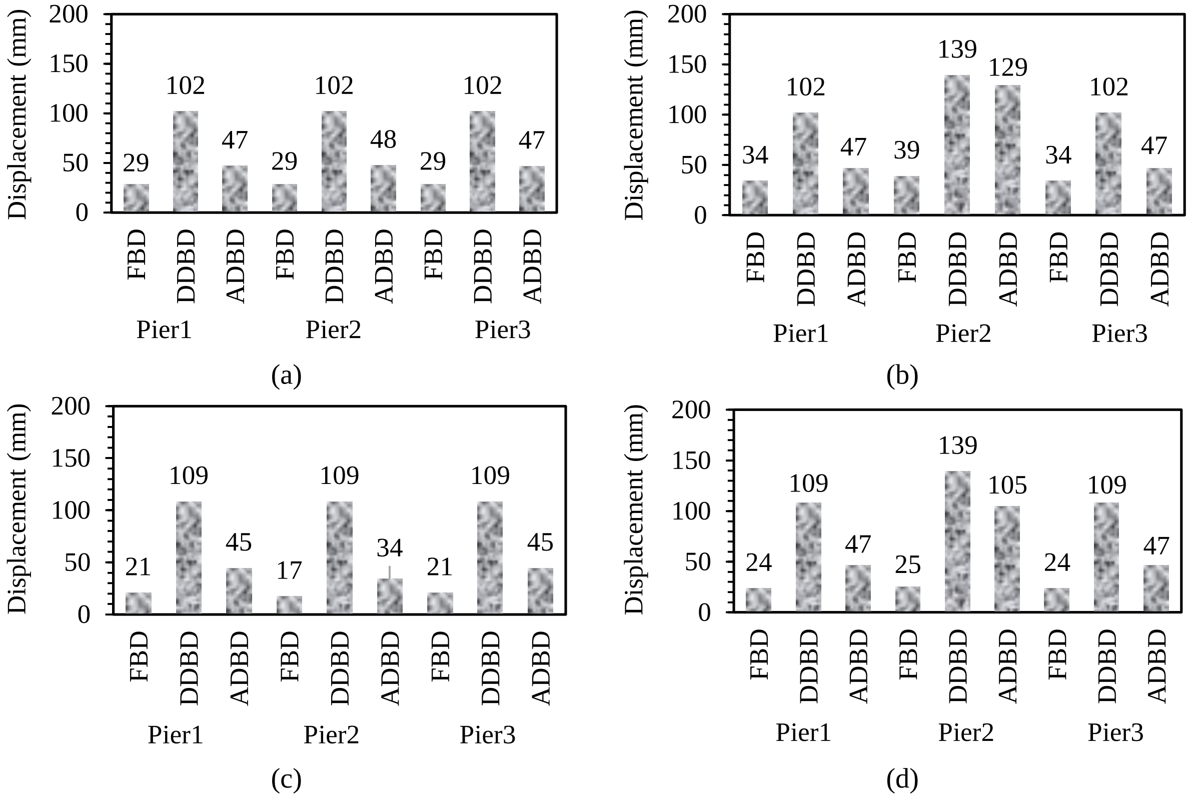
Design Base Shear

The base shear for both models in longitudinal and transverse direction is determined by FBD, DDBD and ADBD methods. Figure 5 shows the comparisons of the base shear in both directions. In the longitudinal direction, DDBD and ADBD estimated 54% and 35% less total base shear respectively than that calculated by FBD for bridge model 1 (Fig. 5a). DDBD and ADBD have estimated 40% and 30% less total base shear respectively than that calculated by FBD for bridge model 2 (Fig. 5b). In the transverse direction, DDBD and ADBD have estimated 38% and 12% less total base shear respectively than that calculated by FBD for bridge model 1 (Fig. 5c). DDBD and ADBD have estimated 38% and 34% less total base shear respectively than that calculated by FBD for bridge model 2 (Fig. 5d).



(a) (b) (c) (d)

Fig. 5: Comparison of design base shear of bridge models; (a) Model 1 - longitudinal direction (b) Model 2 - longitudinal direction (c) Model 1 - transverse direction (d) Model 2 - transverse direction



(a) (b) (c) (d)

Fig. 6: Comparison of design displacement of bridge models; (a) Model 1 - longitudinal direction (b) Model 2 - longitudinal direction (c) Model 1 - transverse direction (d) Model 2 - transverse direction

Design Displacement

The displacement at pier tops for both models in longitudinal and transverse direction is determined by FBD, DDBD and ADBD methods. Figure 6 shows the comparisons of the displacements in both directions. In the longitudinal direction, FBD and ADBD have estimated 72% and 54% less design displacement respectively than that calculated by DDBD for all three piers of equal height in bridge model 1 (Fig. 6a). But FBD and ADBD have estimated 67% and 54% less design displacement respectively than that calculated by DDBD for two outer piers of small height, though FBD and ADBD have estimated 72% and only 7% less design displacement respectively than that calculated by DDBD for the central pier of large height in bridge model 2 (Fig. 6b). In the transverse direction, FBD and ADBD have estimated 81% and 59% less design displacement respectively than that calculated by DDBD for two outer piers of equal height, though FBD and ADBD have estimated maximum of 84% and 69% less design displacement respectively than that calculated by DDBD for the central pier of equal height in bridge model 1 (Fig. 6c). FBD and ADBD have estimated 78% and 57% less design displacement respectively than that calculated by DDBD for two outer piers of small height, though FBD and ADBD have estimated 82% and 24% less design displacement respectively than that calculated by DDBD for the central pier of large height in bridge model 2 (Fig. 6d).

CONCLUSIONS

Displacement-based methods use the displacement spectrum for calculating the base shear force. It is observed that using displacement spectrum needs less step of calculation than using acceleration spectrum of FBD method which makes the calculation easier. From numerical evaluation of two bridge models, it is observed that base shear calculated by DDBD and ADBD is as much as 54% and 35% lesser than that calculated by FBD which makes the pier having less dimension and reinforcement. Again, design displacement estimated by FBD and ADBD is as much as 82% and 59% lesser than that calculated by DDBD. Eventually, FBD method estimates low fundamental period of structures which determines high acceleration resulting high base shear. On the other hand, DBD methods estimate high fundamental period of structures using effective stiffness in place of initial stiffness resulting low base shear and from displacement spectra for high fundamental period high design displacement is obtained. It can be summarized that, DBD methods are more effective than FBD in predicting seismic demand of multispan bridges. DBD methods are introduced with better performance than FBD method in predicting seismic demand of the structure as it designs the structure to achieve a given performance limit state depending on design displacement. In compare to that, FBD requires repetitions of several design steps to achieve desired performance specified by the code.

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