# Global Journal of Engineering Science and Researches <br> STATICS AND KINEMATICS OF ECCENTRICALLY BRACED FRAMES <br> Beeram Sree Keerthe ${ }^{\text {¹ }}$, Sushmita Kadarla ${ }^{1}$ \& Jayaprakash Vemuri ${ }^{2}$ <br> ${ }^{* 1}$ Student, Mahindra Ecole Centrale, College of Engineering, Hyderabad <br> ${ }^{2}$ Assistant Professor, Mahindra Ecole Centrale, College of Engineering, Hyderabad 


#### Abstract

Eccentrically Braced Frames (EBFs) are a suitable seismic load resisting system for seismic areas. EBFs are able to confine damage to the links, which are easily replaceable after severe earthquakes. However, the EBF has not adopted widely in India since the current Indian Steel Design Code, IS 800:2007, provides no guidance on the design of EBFs. In this paper, equations to understand the statics and kinematics of EBFs are established. The effect of frame geometry is examined and key parameters affecting EBF structural response are identified.


Keywords: statics, kinematics, frame geometry, steel design, eccentrically braced frame.

## I. INTRODUCTION

The Eccentrically Braced Frame (EBF) is a lateral load-resisting system which combines high stiffness with ductility and energy-dissipation capacity (Vemuri, 2014; Vemuri, 2015). Figure 1 shows the key members of an Eccentrically Braced Frame. Links are designed to respond in-elastically during an earthquake. Typically, the link strain hardens and reaches its ultimate shear / flexural capacity, which is higher than the nominal plastic shear / flexural capacity based on the nominal / actual yield strength (Vemuri, 2016; Vemuri, 2017). The non-fuse elements are intended to behave elastically during a seismic event and so are proportioned using capacity-based design for the maximum capacity of the link.


Fig. 1: Members in an Eccentrically Braced Frame

## II. STATICS OF AN ECCENTRICALLY BRACED FRAME

Figure 2 shows the free body diagram necessary to derive the link shear in an EBF due to seismic forces. Assuming all connections are pinned, Equations [1] to [6] are derived as simple applications of force and moment equilibrium of a plane frame.

Moment equilibrium about Point A requires the shear force in the link to be
$V_{f}=\frac{h}{L} V_{c}$
where $V_{c}$ is the factored horizontal storey shear force due to seismic loads, $h$ is the storey height and $L$ is the frame span length as shown in Figure 2a). The shear force in the link beam outside the link, $\mathrm{V}_{\mathrm{b}}$, can be determined by considering moment equilibrium of the beam about its intersection with the brace, Point C in Figure 2 b ) assuming the brace is pinned to the beam:
$\mathrm{V}_{\mathrm{b}}=\mathrm{V}_{\mathrm{f}} \frac{\mathrm{e}}{\mathrm{L}-\mathrm{e}}$
The axial force in the brace, $\mathrm{P}_{\mathrm{br}}$, is obtained considering vertical force equilibrium at Point C in Figure 2(a):
$P_{b r}=\frac{V_{b}+V_{f}}{\sin \beta}$
where $\beta$ is angle between the brace and the link beam as shown. The axial force in the link beam, $\mathrm{P}_{\mathrm{b}}$, can be computed considering horizontal force equilibrium of Point C :
$\mathrm{P}_{\mathrm{b}}=\mathrm{P}_{\mathrm{br}} \cos \beta=\mathrm{V}_{\mathrm{c}}$
Finally, the axial force in Column A-B, $\mathrm{P}_{\mathrm{c}}$, is computed considering vertical force equilibrium at Point B :
$P_{c}=P_{c u}-P_{b r u} \sin \beta+V_{b}$
[5]
Here, $\mathrm{P}_{\mathrm{cu}}$ and $\mathrm{P}_{\mathrm{bru}}$ are axial forces in the column and brace, respectively, immediately above Point B. Note that the shear in the link beam always counteracts the vertical component of the brace force.

If the connection between the brace and the link is not assumed pinned, the distribution of the link moment to the link beam and the brace depends on their relative stiffnesses accounting for their end restraints and on whether the link beam is elastic or plastic at its connection with the brace and link. The link end moment not carried by the linkbeam must be resisted by the brace:
$M_{b r}=M_{e}-M_{b}$
where $M_{e}=V_{f}$. eis the total moment at the end of the link and $M_{b r}$ and $M_{b}$ are the moments transferred in the brace and the link-beam, respectively. The brace is designed to resist the combined effects of $\mathrm{P}_{\mathrm{br}}$ andM $_{\mathrm{br}}$.

(b)

Fig. 2: Statics of an EBF (a) Shear force in link (b) Forces at link-brace-link beam joint

## III. KINEMATICS OF AN ECCENTRICALLY BRACED FRAME

The inelastic link rotation be limited to ensure the rotation capacity of the ductile link is not exceeded. This requirement also limits the ductility demand on the frame. Figures 3 (a) and (b) show a rigid-plastic sway mechanism in a K-braced frame. Assuming a rigid - perfectly plastic material response with rotations confined to the plastic hinges at each end of the link, the link rotation angle, $\theta$, between link and the link beam is determined from the lateral deflection and frame geometry (Becker and Ishler, 1996). From Figure 3(b), the overall sway geometry gives:
[I-CONCEPTS-18]
$\theta_{1}=\frac{\delta}{h_{1}}$
$\theta_{2}=\frac{\delta}{h_{2}}$
where $\delta$ is the design drift for the EBF, $\mathrm{h}_{1}$ and $\mathrm{h}_{2}$ are the respective column heights, and $\theta_{1}$ and $\theta_{2}$ are the rigid-body rotation, of the left and right sides of the frame, respectively.
The vertical link beam deflections at the ends of the link are:
$\delta_{1}=\theta_{1} \cdot a_{1}$
$\delta_{2}=\theta_{2} \cdot a_{2}$
[8a]
[8b]
where $a_{1}$ and $a_{2}$ are the lengths of the respective link beams. From the deformed shape at the left end of the link: $\theta=\theta_{1}+\frac{\delta_{1}}{e}+\frac{\delta_{2}}{e}$

(a) Deformed shape; plastic hinges (b)the angles between the members

Fig 3: Rigid-plastic mechanism in a K-braced frame (Becker and Ishler, 1996. Used with permission).
Using [7a], [7b], [8a] and [8b] to eliminate $\delta_{1}$ and $\delta_{2}$ from [10]:
$\theta=\theta_{1}+\frac{\delta . \mathrm{a}_{1}}{\mathrm{~h}_{1} \mathrm{e}}+\frac{\delta . \mathrm{a}_{2}}{\mathrm{~h}_{2} \mathrm{e}}$
[10]
For a symmetric configuration, i.e. $a_{1}=a_{2}=a$ and $h_{1}=h_{2}=h$, Equation [10] reduces to
$\theta=\frac{\delta}{\mathrm{h}}\left(1+\frac{2 \mathrm{a}}{\mathrm{e}}\right)=\frac{\delta}{\mathrm{h}}\left(\frac{\mathrm{e}+2 \mathrm{a}}{\mathrm{e}}\right)=\frac{\delta}{\mathrm{h}} \frac{\mathrm{L}}{\mathrm{e}}$
[11]

## IV. EFFECT OF FRAME GEOMETRY

The frame geometry is essentially dictated by three factors, the inter-storey height, h the link length,e and the span length, $L$. These three factors define the angle between the brace and the beam, $\beta$, which, as described previously, controls the distribution of the axial forces in an EBF (as shown in Equation [3] and [4]). A higher axial force in the link beam reduces its flexural capacity, thus requiring the brace to take more moment (Equation [6]). This may lead to premature brace yielding. Typical values of $\beta$ range from $30-55$ degrees (Becker and Ishler, 1996).

The link rotation angle depends entirely on the storey drift and geometry of the structure as shown in Equation [11]. From Equation [11] it can be inferred that the link rotation angle, $\theta$ is inversely related to the link length,e. Short links, with smaller normalized link lengths, e/L, undergo large rotations and thereby exhibit greater overstrength due to strain hardening, compared to long links. Typically, while the height and span of the frame is decided by practical considerations, the designer can choose a suitable link length, e, to control the link rotation angle. For
example, as the span $L$ increases, the length of the link beam, a also increases. For a given frame height, hand frame drift, $\delta$, a longer link length e can be selected to limit the link rotation angle, $\theta$.

## V. CONCLUSIONS

The Eccentrically Braced Frame (EBF) is a seismic load resisting system, which has both high stiffness and high energy dissipating capacity. However, the EBF has not adopted widely in India since the current Indian Steel Design Code, IS 800 (Bureau of Indian Standards, 2007) provides no guidance on the design of EBFs. To establish the design criteria for EBFs, it is essential to establish the equations of mechanics and kinematics. The equations derived in this paper for understanding the statics and kinematics of an EBF can aid in the computation of forces in the ductile link elements and other non-ductile members. Further, in this paper, key parameters, such as link length, link rotation and which effect the structural response of EBFs are identified.

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