Efficient Application of Rocking Motion in Design of Steel Structures

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SUMMARY: (10 pt)
Despite extensive research efforts in seismic design of modern structural systems, their industrial application in engineering structures is taken for granted. On the other hand, the adequately designed modern structures subjected to earthquake ground motion can provide significant advantage over their conventional counterparts. For example, extensive damage distributed throughout the main structural members and post-earthquake residual drifts are in charge of making post- earthquake repair of such structural systems a costly and time-consuming or even impossible process. On the contrary, application of modern earthquake-resistant structures can provide superior performance as well as economic repair cost for buildings located in seismic areas. In this paper, a special kind of modern steel structures which are allowed to have rocking motion by experiencing certain amount of uplift at their column bases have been studied. The seismic response of structures is studied through nonlinear dynamic analysis. The validity of the numerical simulation is verified by applying the model to previous experimental studies in the literature. The efficiency of the aforementioned techniques in reducing seismic demand of steel structures are discussed to develop their usage in common practice.

Keywords: Rocking motion, modern structures, residual drift, damage

1. GENERAL INSTRUCTIONS

Due to their simple and economic usage, Steel Braced Frames (SBFs) have been extensively used as the most usual type of earthquake-resisting systems for steel structures. On the other hand, severe post-earthquake damages associated with concentrated residual drifts make the repair of such structural systems a costly and time-consuming or even impossible process. Thus, significant efforts have been made to develop modern structural systems as serious rivals for their conventional counterparts in order to reduce the seismic damages of buildings subjected to severe earthquake motions in the last decades. As an instance, it was pointed out that the effects of rocking vibration accompanied with uplift motion may reduce seismic damage of buildings after major seismic events [1-2]. Besides, several experimental and numerical studies have been performed by various researchers to investigate seismic performance of steel rocking frames [3-10]. As shown in Figs. 1 and 2, two typical steel rocking frames proposed by former researchers are considered as the basis for the present study [6], [10]. In the Base Plate Yielding (BPY) rocking system the energy dissipation and self-centering mechanisms are provided by yielding of weak base plates that experience uplift motion during earthquake and gravity loads, respectively. In the single rocking frame the column bases are free to uplift during earthquake and the energy dissipation and self-centering mechanisms are provided by replacable shear fuses and Post-Tensioning strands (PT), respectively. It should be noted that various alternatives have been proposed to be used as steel fuse elements with flextural and shear yielding mechanisms by previous researchers [11-13], but in the present study butterfly fuses which have been recently tested extensively are considered [7] ,[14].

Although promising research studies have been done on the performance of rocking steel frames, their industrial application in engineering structures is taken for granted. For instance, despite extensive numerical and experimental studies on the BPY systems the seismic demand reduction was compared with a conventional braced frame which remained elastic during the tests which is not the case in a major seismic event [6]. In fact several nonlinear time-history response procedures of much more code-conforming conventional braced frames as well as their rocking counterparts should be studied in order to develop their usage in the common practice. In the present study, typical structural systems adequately designed by professional engineers according to the latest seismic design provisions are compared to the rocking systems through nonlinear time-history analysis. In addition, the selected earthquakes by the previous researchers ([10]) based on the far-field record set as proposed by FEMA P695 is selected as the basis of the analytical procedure to take into account the record to record variability and uncertainty of earthquake phenomenon [15]. The peak median response parameters are obtained by fitting a log-normal distribution to the analytical results of the individual earthquake records. The Lilliefors test is used as the goodness-of-fit test to check the adequacy of the presumed lognormal distribution of the data [16]. It should also be noted that significant effort is made to verify analytical simulations with the previous published test data to ensure validity of numerical models.

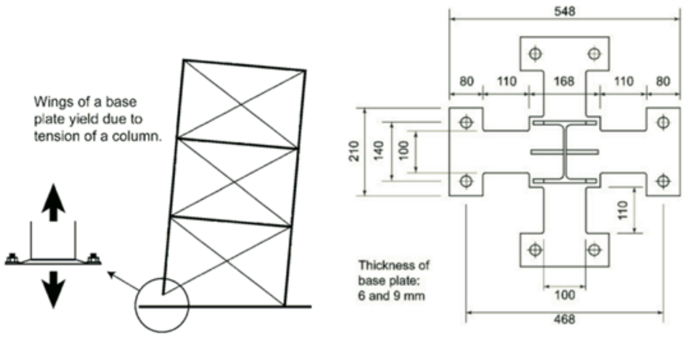

Figure 1. Base Plate Yielding (BPY) rocking system [6]: (a) configuration, (b) base plate detail

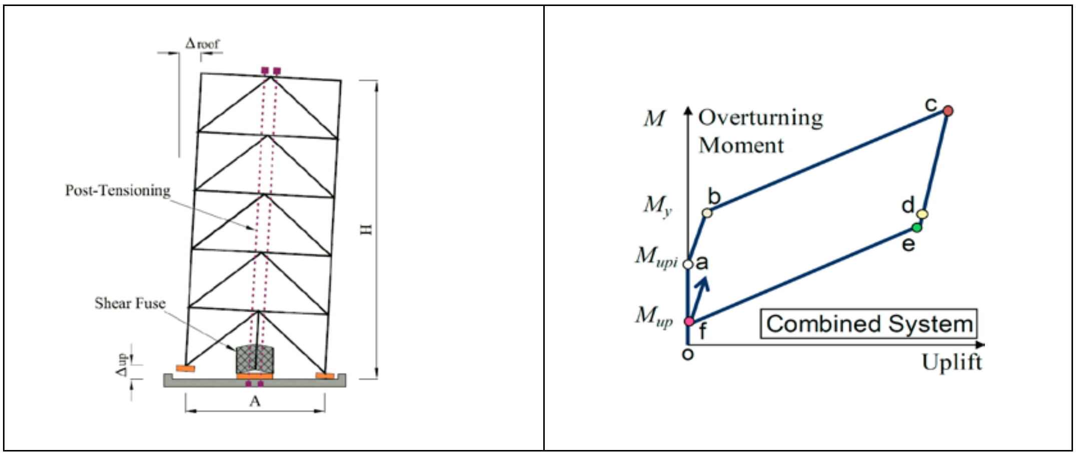

Figure 2. Single rocking system [10]: (a) configuration, (b) backbone curve

2. APPLICATION EXAMPLE

The basic prototype building to investigate seismic performance of conventional and rocking steel frames is shown in Fig. 3. This building configuration is the same one which is used in the SAC Joint Venture Project [17]. It is a three-story, four bay × six bay building with typical floor and roof framing, assumed to be located near Los Angeles, California. This building selected as the basis of the present research to match the previous numerical studies and to ensure the adequacy of obtained results from nonlinear time-history simulations in comparison with the published results [10].

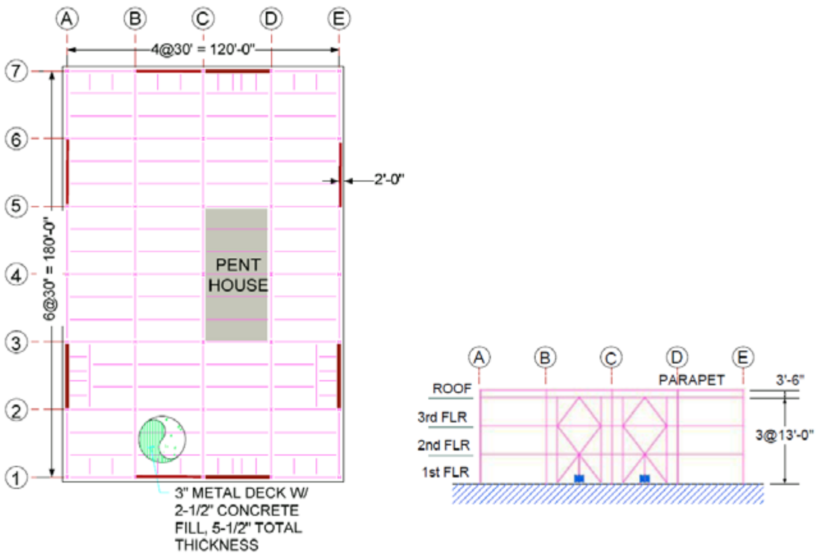

Figure 3. Prototype building [10] , [17] (a) typical plan, (b) elevation

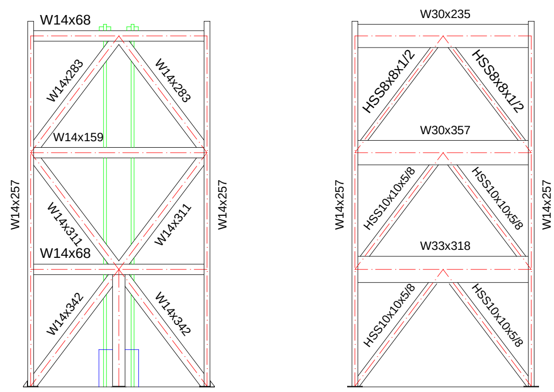

Figure 4. Structural system specification for original (3-story) building (a) single rocking [10], (b) IVBF

Also, the earthquake-resisting units may be either conventional Inverted-V Braced Frames (IVBFs) or Single Rocking Systems (SRS) with butterfly fuses which are assumed to be located in the selected bays of the perimeter of the building and all other columns are only gravity-bearing ones that do not contribute in the earthquake-bearing structural system [10], [14]. Conventional IVBFs are adequately designed and the structural members are proportioned in the preliminary design process. Required frame member forces are established following the conventional building code approach (ASCE7, 2005) [18]. The preliminary design and proportioning structural member's process for the rocking frames and base detailing can be found elsewhere [10]. As an instance, final configuration of design process for one of the earthquake-resistance units of the IVBF and SRS in the case of 3-story building is presented in Fig. 4.

3. ANALYTICAL PROCEDURE AND MODEL VERIFICATION

Analytical procedure of the aforementioned structures is conducted using the open-source software OpenSees [19]. The proposed models are 2D ones, and beam-column elements with co-rotational transformation are used to take into account both geometric and material nonlinearities. Leaninig columns are also added in the analytical models to represent gravity frames simulating P-Delta effects on the response of the frames. It should be noted that in the case of IVBFs force-based nonlinear beam-column elements are used to simulate buckling response of the bracing members. Each bracing member must be divided into at least two elements and a value of L/1000 is selected for initial imperfection. Each cross-section of bracing members is divided into rectangular areas and 10x10 fiber mesh is assigned to each of them. Compact sections are selected for the members to avoid inadequacies related to not considering local buckling in the modeling process. More details about modeling techniques can be found elsewhere [20], [21].

In the case of rocking systems the basic modeling techniques and calibrated models for simulating elements such as fuse, PT elements are selected from the relevant published documents [6], [10]. The gap elements with a high stiffness in compression and no stiffness in tension are used to simulate uplift-allowing rocking bases. Material properties and mechanical specifications of the fuse and PT elements are calibrated based on the previous test data [6], [10], [14]. It should be noted that in the case of rocking system calibrated simplified fuse model as proposed in the literature is adopted to avoid unnecessary complications in the modeling procedures [10]. The previous results and present study conclusion revealed that the obtained results are in the acceptable range for non-buckling fuses with a much less computational cost. In addition for the BPY case it is proved in the present study that the proposed simple analytical approach is a much more effective one on the expense of possible minor inadequacies in the obtained results compared to the detailed finite element model in the reference [6] which incorporates shell elements simulating column bases and first-story columns.

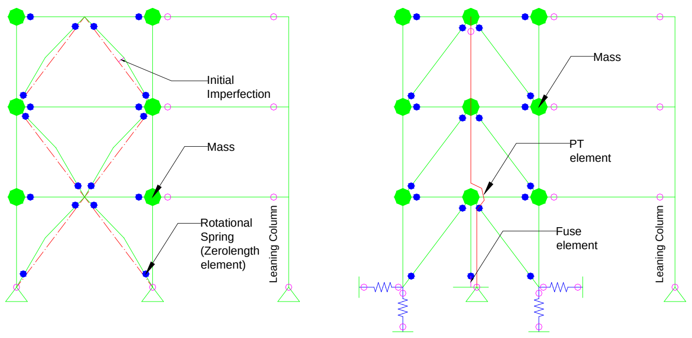

Figure 5. Proposed finite element models for original (3-story) building (a) IVBF, (b) single rocking

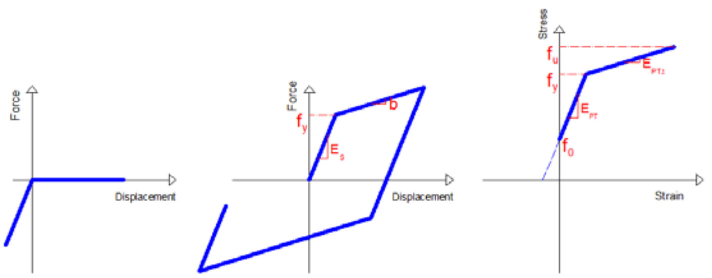

Figure 6. Material models: (a) elastic no tension, (b) calibrated steel fuse, (c) PT component

In the present study rayleigh damping is selected to simulate damping in the time-history analysis procedure. It should be noted that damping simulation in the nonlinear analysis is a somewhat controversial subject that more discussion about this issue can be found elsewhere [22-24]. Here, because of the necessity of comparing the results, the same assumptions in the literature are adopted in each case [6], [10]. The proposed model for 3-story IVBF and SRS systems are presented in Fig. 5. Material models of the members are presented in Fig. 6. Finally, it should be mentioned that much effort is done to validate and verify the analytical models both at the component and system levels. In this way, the predicted response of the analytical tool is compared with various available test data in the literature of steel frames ([6], [10], [25]) which only some of them are shown in Fig. 7. On this basis the ability of the analytical model in predicting the structural response of such structures is verified.

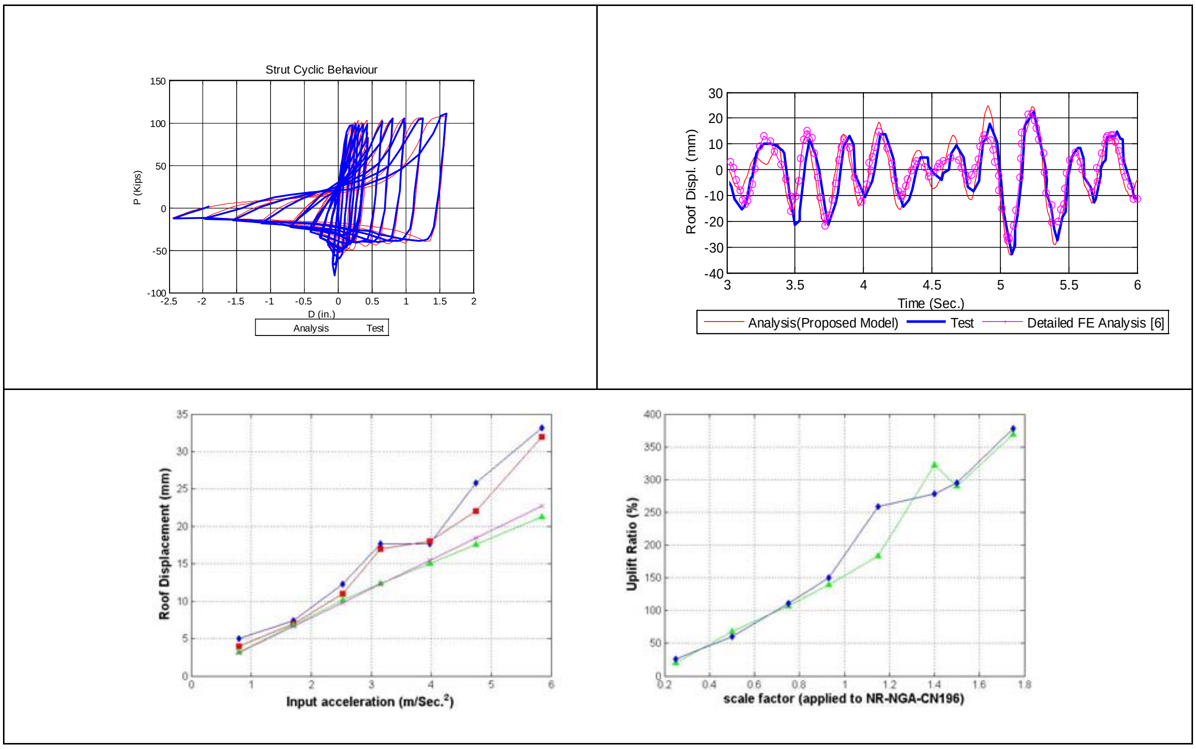

Figure 7. Verification of proposed model (a) cyclic response (buckling brace, pipe section) [25], (b) Time-history of roof displacement at 5.84 m/sec.2 input acceleration (BPY system) [6], (c) Peak roof displacement at various input acceleration (BPY system) [6], (d) Uplift ratio at various scale factors (SRS system) [10]

4. ANALYTICAL RESULTS AND CONCLUSIONS

Based on the obtained results of numerical aforementioned simulation valuable information is got about the superior performance of rocking system compared to the conventional structure both designed for the same typical building. Among all of the results, only a few of them are represented in Figs. 8-10. Time-history response of story drifts of IVBF and SRS systems for two selected earthquakes at the MCE level are presented in Figs. 8 and 9, respectively. This is true because of significant reduction in the net inter-story drift ratio in the rocking structure due to dominate rigid body rotation. It can be seen that the value of peak story drift is less than 0.5 % for these records in the case of rocking system but it is about 4 % for the IVBF system. Another important feature is less residual drift in the case of rocking frame.

It can be seen that for the case of IVBF the maximum value of the drift has been occurred in the first story. This is because of more severe buckling in the first story braces due to larger seismic demands. On the other hand the rocking system has experienced almost uniform story drifts throughout its height due to dominate rigid body rotation. In the most cases upper stories have got minor additional drifts due to elastic deformation of the structure.

For the aim of comparison, median responses of first story peak story drift of IVBF system subjected to the selected record set by the former researchers [10] is presented in Fig. 10. It can be seen that the median value of peak story drift of IVBF at the DBE level is about 1.5% which is about 3 times the reported corresponding value for the case of SRS system [10].

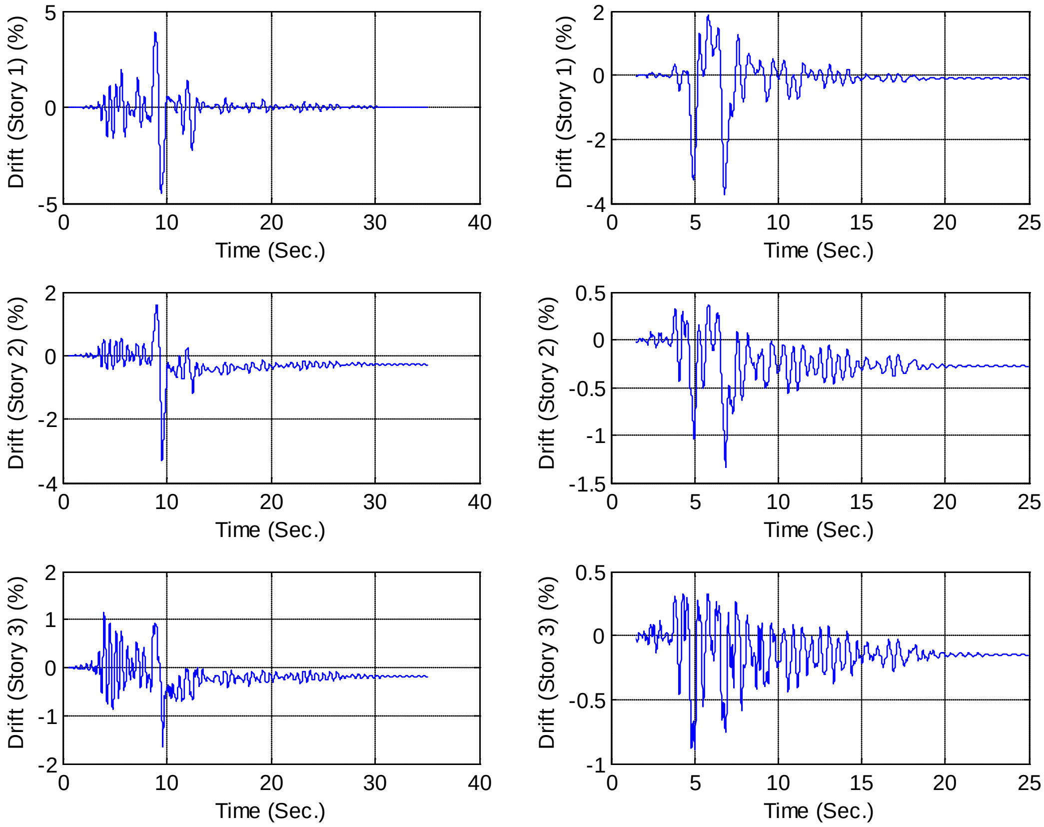

Figure 8. Story drift of IVBF subjected to MUL-279 (left) and LOS000 (right) earthquake records at MCE level

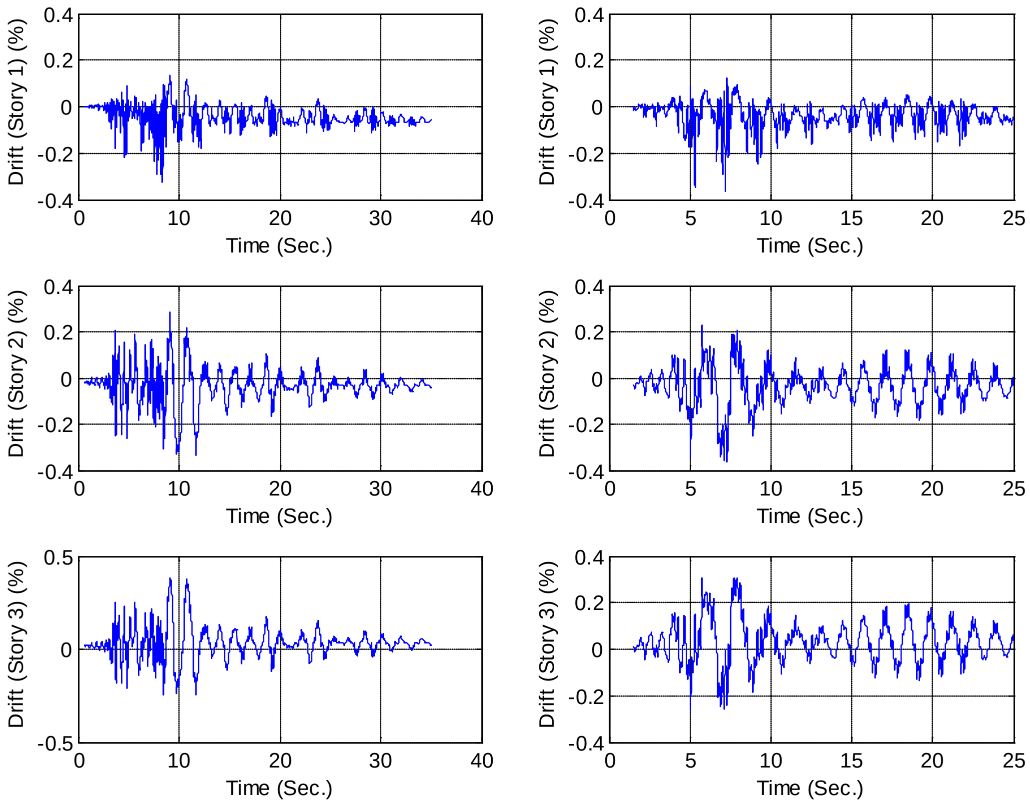

Figure 9. Story drift of SRS subjected to MUL-279 (left) and LOS000 (right) earthquake records at MCE level

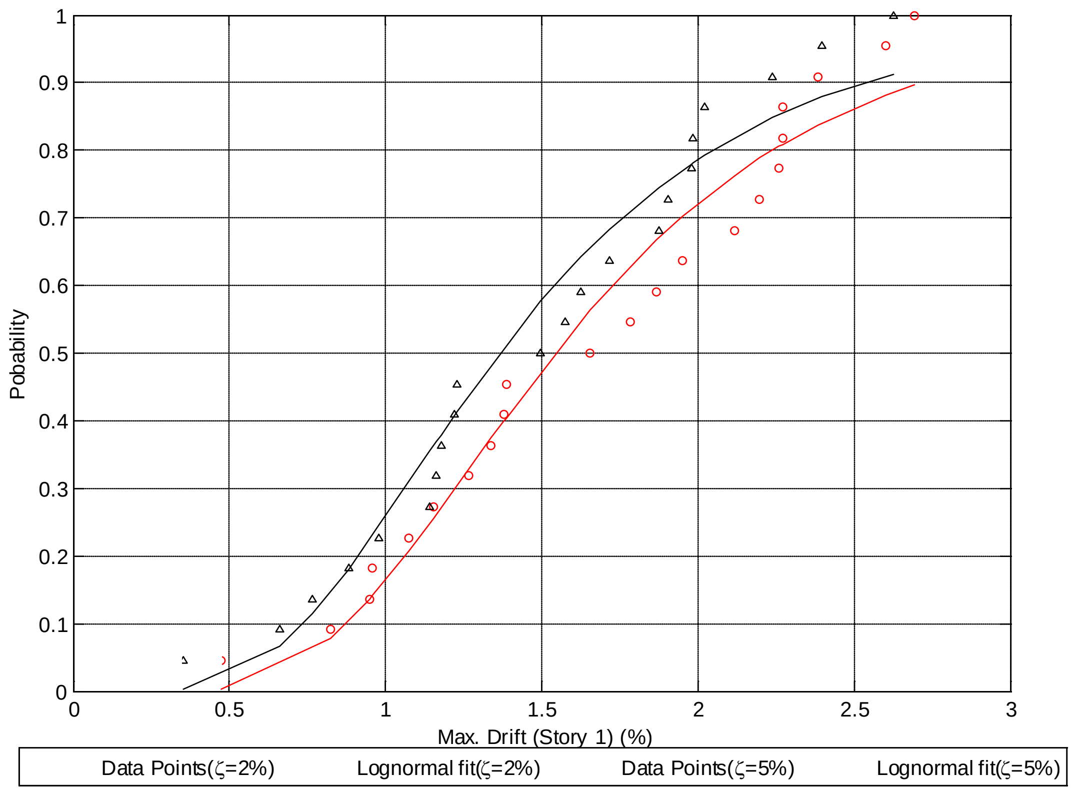

Figure 10. Median response of IVBF subjected to record set scaled to DBE

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