Comparison of the Approaches Used for the Evaluation of Accidental Load Drops in Nuclear Power Plant Structures

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Abstract

An accidental load drop during load handling could impact the safety of the nuclear plant structures or safety-related equipment and cause inadvertent criticality, or loss of safe shutdown equipment. In this paper, available approaches for evaluation of the structural members due to impact of an accidental load drop in US nuclear power plants are evaluated. Consideration is given to the limitations of the approaches imposed by the NUREG-0612 (1980). The paper discusses the two common approaches that can be used to evaluate the impact: the first approach is to calculate the elasto-plastic energy absorption capacity of the member and compare it to the energy imparted during impact. The second is to estimate the applied force on the impacted member considering the penetration of the load into the target using empirical formulas. The limitations of each approach are demonstrated by evaluation of a hypothetical structural beam. Both approaches are investigated to calculate the allowable load at a given drop height for various drop locations along the beam centerline, as well as off-centerline of the beam. Additionally, a sensitivity study is performed to consider the effect of boundary conditions on the results in terms of the load drop capacity. Based on the results of the analysis, recommendations are given for the proper selection of the approach to estimate the allowable drop load based on the load drop location.

INTRODUCTION

The regulatory requirements for the evaluation of structural members for accidental load drops are given in Appendix A of NUREG-0612 (1980). However, the considerations given in Appendix A limits the calculated capacity of the SSCs for postulated load drops. For example, one of the requirements is that the load may be dropped at any orientation in the crane travel area where movement is not restricted by mechanical stops or electrical interlocks. Therefore, evaluation of the load drop needs to consider all possible load drop locations on the target. As it will be shown in this paper, the energy absorption capacity of the target will become negligible for the cases where the load is dropped close to the target supports, due to small flexibility of the supports, which can result in unrealistically high impact load. Another requirement given in Appendix A is to postulate "maximum" damage that could result due to the drop, i.e., the analysis should consider that all energy is absorbed by the structure and/or equipment that is impacted. As a result, no credit can be taken for the dissipated energy due to inelastic deformation or crushing of the dropped load, which means that the load has to be treated as 'rigid' regardless of its deformations. Moreover, due to this restriction, conventional methods that consider the energy loss due to the conservation of momentum are not applicable for the evaluation of accidental load drops. Due to the limitations imposed by NUREG-0612 (1980), as well as some identified lack of consistencies in plant licensing bases, the Nuclear Strategic Issues Advisory Committee approved an industry initiative on September 2007, to address concerns regarding the interpretation and implementation of the regulatory guidance associated with heavy load lifts. The new guidelines are provided in NEI 08-05 (2008). These guidelines are more specifically tailored towards the analysis of the reactor vessel head and spent fuel cask lifts against drops over the spent fuel pool, where the consequence of an accidental drop can be the most significant, and the considerations given in NEI-0612 (1980) could become impractical due to the extremely heavy weight of these components. From the structural analysis point of view, some of the major differences between the NEI-0612-Appendix A guidelines and the new NEI 08-05 (2008) guidelines are as follow:

- Contrary to the NEI-0612, which requires a load drop orientation that causes the most severe consequence, the NEI 08-05 (2008) considers the reactor vessel head drop as concentric and directly on the vessel flange.
- NEI 08-05 (2008) does not require the analyses to be based on elastic-plastic curve that represents a true stress-strain relationship. However, if the analyses are based on an elastic-plastic curve, it must represent a true stress-strain relationship.
- Contrary to the NEI-0612 requirements, analyses that account for appropriate consideration of conservation of momentum are acceptable. It is also acceptable to consider damping.
- Contrary to NEI-0612 which requires the dropped load as rigid, the NEI 08-05 (2008) allows the deformation of the Reactor Vessel head to be considered, if explicitly modeled. Additionally, the deformation of components attached to the RV head may be realistically considered.

The article presented herein does not consider the criteria given in NEI 08-05 (2008) as they are more specifically tailored towards the Reactor Vessel head and spent fuel cask drop analysis. Rather, it presents the general approaches that can be used to meet the criteria given in NEI 0612-Appendix A.

An accidental heavy load drop can result in both local damage as well as overall failure of the target structure being impacted. The local damage is more critical for concrete structures than steel, and may consist of spalling of concrete from the front (impacted) face and scabbing of concrete from the rear face of the target together with load penetration into the target. Overall dynamic response of the target mainly consists of flexural deformations. A potential flexural or shear failure will occur if the strain energy capacity of the target does not exceed the kinetic energy input by the striking load.

Upon identification of all heavy loads, including identification of the weights, dimensions, material properties, and structural characteristics, and the locations where they are handled, load drop scenarios based upon realistic consideration of plant procedures are evaluated to identify loads which control:

1- Local response (e.g., penetration, scabbing, spalling, perforation, etc);
2- Overall structural response (e.g. large inelastic deformations or abrupt failures of principal structural members, etc);

The evaluation methodology and criteria generally follows the recommendations made by the American Society of Civil Engineers (ASCE), Technical Committee on Impulse and Impact Loads (1980). These recommendations are supplemented by a large body of experimental and analytical information which is documented in reports which have been published by government, university, and industry organizations.

LOCAL EFFECT EVALUATION

Local impact may lead to severe damage in the vicinity of impactive load. The penetration of an impactive load into a resisting mass is governed by the velocity of the impact, the physical properties of the dropped load, and the material characteristics of the resisting mass. The complex nature of local impact response requires evaluation using empirical formulas that are experimentally derived. The most commonly known formulas are modified Petry formula (see Amirikian (1950), the Army Corps of Engineers (1946) formula, the modified National Defense Research Committee (NDRC) (1946) formula, the Amman & Whitney formula, and the Ballistic Research Laboratory formula (see Gwaltney (1968)).

All of these empirical equations are strictly applicable only to the condition of an essentially non-deformable dropped mass and target and are thus expected to over-predict local effects for deformable target. A comparison of these empirical formulas is made by Kennedy (1976), which concludes that for the case of non-deformable impactive mass and rigid reinforced concrete targets, the modified NDRC formula should be used rather than other methods. The NDRC formula has the advantage of being based upon an approximate theory of penetration rather than being purely empirical one, thus giving greater confidence in the extrapolation of its results.

The NDRC formula for the depth of penetration, X (inches), of a solid cylindrical mass into reinforced concrete is given by:

$$X = \left[4KNWd\frac{V^{1.8}}{1000d}\right]^{1/2} \quad \text{for} \quad \frac{X}{d} \leq 2.0$$

or (1)

$$X = KNW\left[\frac{V}{1000d}\right]^{1.8} + d \quad \text{for} \ \frac{X}{d} \geq 2.0$$

where
$W =$ weight of the dropped mass (pounds)
$d =$ diameter of dropped load (inches)
$V =$ impact velocity of the load (feet/second)
$N =$ load shape factor (0.72 for flat nosed objects)
$K = \frac{180}{\sqrt{f'_c}}$ (f'_c=concrete compressive strength in psi)

The effect of shape and deformability for non-circular loads can be accounted for by using equivalent diameter that results in the same area as the smallest nose face of the impactive mass.

For the steel targets, there are fewer empirical formulas available. The most common formula is known as the Ballistic Research Laboratory (BRL) (see Miyamoto et al. (1979)) formula as presented herein:

$$X = \frac{0.5W.V^2}{17400.g.d^{3/2}} \qquad (2)$$

GLOBAL EFFECT EVALUATION

The dropped loads are capable of producing gross and intolerable deformations of primary structural members and possibly propagating failures. A discussion of overall structural response evaluation techniques is provided herein.

Global Effect Evaluation Using Dynamic Force

The forcing function can be estimated by incorporating characteristics of the dropped load, characteristics of the target structure (material properties, structural configuration), and the impact conditions (velocity, orientation). Unfortunately, insufficient data is available to permit the prediction of the size and shape of the typical loads. However, by discussions with the utility, the engineer may assume a reasonable size for the dropped load at a given location for a specific lifting event, by discussions with the utility.

The procedure proposed herein provides a means of calculating an equivalent static load which will permit the designer to establish the required capacity of the structure to resist the load resulting from an accidental drop. The basic assumption made is that the velocity of the impact load, V, reduces linearly to zero as the load penetrates into the target, resulting in a rectangular pulse loading. The total kinetic energy of the dropped load is expended while the load travels a distance X equal to the penetration obtained by either of the formulas described previously. The deflection of the structure should conservatively be neglected since the empirical formulas that provide the penetration are based on the experiments on rigid targets.
Under these assumptions, the loading applied to the structural element is determined by equating the work done by dropped load as it penetrates the structure, to the initial potential energy of the load. i.e.

$$F = \left(\frac{W.h}{X}\right) \qquad (3)$$

where
F = Dynamic force due to the load drop (A rectangular pulse)
W = Weight of the object being dropped
h = Drop height
X = Penetration depth calculated from empirical formula

It should be noted that the force F is a dynamic force. In order to apply this load in a static manner, it is convenient to introduce the concept of the Dynamic Load Factor (DLF). This factor is determined as the ratio of the dynamic deformation at any time to the deflection which would have resulted from the static application of the load F. Since the deflections and stresses in the structure are all proportional, the dynamic load factor may be applied to any of these in order to obtain the ratio of dynamic to static effects. As shown in Biggs (1964), the DLF is a function of the ratio of the loading duration to the primary period of the structure. The DLF for various load functions can be found in Biggs (1964).

Global Effect Evaluation Using Energy Balance

For the case where the load impact results in little or no penetration, the preceding method cannot be used. As an alternative, a method based on the energy absorption capacity of the target should be utilized. The energy balance approach incorporates the conservation of energy to calculate the transmitted kinetic energy and maximum displacement to investigate the primary failure modes (shear or flexure) of the impacted structure. The advantage of this technique is that it does not require explicit knowledge of the forcing function.

The original derivation of the method is given by Timoshenko (1937) and is carried on a single degree of freedom (SDOF) mass-spring system replacing the actual structure.

The objective of the energy balance approach is to characterize structural behavior in terms of the available strain energy up to prescribed performance deflection limits. The maximum deflection limit is calculated by multiplying the yield displacement by the ductility limit μ. The ductility limit is defined as the ratio of the ultimate allowable deflection of the structural member to the deflection corresponding to the effective yield. The ductility limit is dictated by the mode of failure, which is ductile in case of flexure and brittle in case of shear failure. These limits are defined in the applicable design codes such as AISC N690 (2006) and ACI 349 (2006). For example, AISC N690 (2006) provides the following ductility limits for structural steel members: μ=20 if flexure controls for closed section; μ=12.5 if flexure controls for open section; μ=5 if shear controls. ACI 349 (2006) provides the following ductility limit for concrete members: $\mu = \frac{0.05}{\rho - \rho'} \leq 10$ if flexure controls; and μ = 1.3 if shear controls, where ρ = tension reinforcement ratio and ρ' = compression reinforcement ratio.

The energy absorption capacity can be calculated by considering the area under the elastic-plastic load deflection curve of the structural element of interest. For simplicity, an effective elastic-perfectly plastic force-displacement curve can be developed for the target structure as shown in Figure 1. The effective yield displacement d_y, which corresponds to the inflection point of this effective elastic-perfectly plastic curve can be conservatively considered equal to the minimum yield displacement.

The above mentioned approaches are compared on a typical reinforced concrete beam supporting a one-way slab. The following sections describe the system and the results of the evaluation.

CASE STUDY

A reinforced concrete beam supporting a 16'x30' one-way slab is evaluated for maximum permissible load weight that can be lifted and carried at 1 ft. above the slab top surface. The properties of the beam are shown in Table 1 below:

The beam-slab was modeled in Finite Element (FE) program SAP2000 using 3D shell elements for the slab, and beam elements for the supporting beams. The schematic of the FE model is shown in Figure 2. Two different models were developed to consider the effect of boundary conditions. The first model considers the beam and the slab ends to be fixed. The second model considers the beam and the slab ends as pinned. These models were used to obtain the maximum shear, moment and torsion response of the beam against a unit load at various locations. The unit load responses were then used to obtain the stiffness, as well as the total response of the system for any given impact load.

Various load drop locations are considered in this study. These locations are chosen to approximately cover the entire area of the slab. These locations are shown on the slab plan view in Figure 3.

ACI 349 (2006) was used to evaluate the flexure as well as shear capacity of the beam. The moment and shear capacities were then used to calculate the maximum permissible concentrated load, R_m which is the amount of concentrated load that causes the beam to fail in flexure, or in shear, whichever occurs first at the given drop location. It is assumed that the slab has adequate capacity to take the load resulting from drop impact. Therefore, only the beam capacity is evaluated in this study.

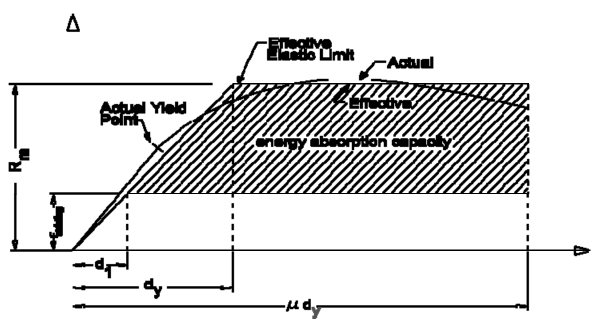

Figure 1: Actual vs. Idealized (effective) load deflection curve of an elasto-plastic system

Table 1: Beam and slab design details

beam width	12 in.	rebar yield strength*	60000 psi
beam height	24 in.	bottom longitudinal	3 No. 11 bars
slab thickness	10 in.	top longitudinal steel	3 No. 11 bars
total length	30 ft.	stirrups	No. 5 @ 10

slab total width	16 ft.	design criteria	ACI 349
concrete clear cover	1.5 in.	beam moment capacity	438.68 kip.ft
concrete 28 day*	4000	beam shear capacity	75.83 kip

(*) Per ACI 349 (2006), a dynamic increase factors (DIF) appropriate for the strain rates involved may be applied to static material strengths of steel and concrete for purposes of determining section strength. A DIF of 1.25 for flexural compression of concrete, 1.1 for concrete in shear and 1.1 for reinforcing steel is permitted in ACI 349 (2006) and is used in this study.

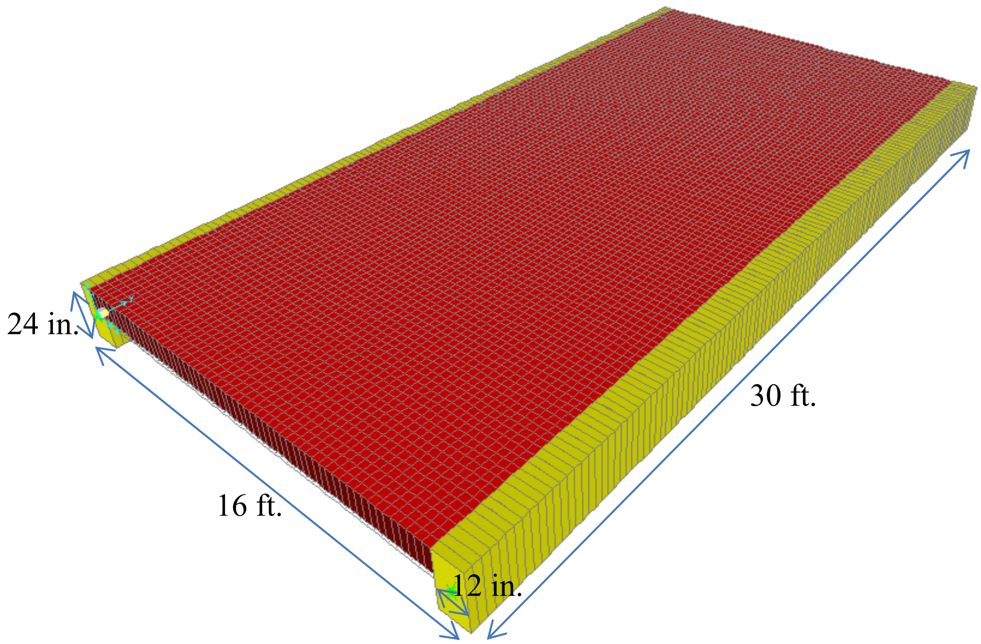

Figure 2: Schematic of the FE model showing the overall dimensions

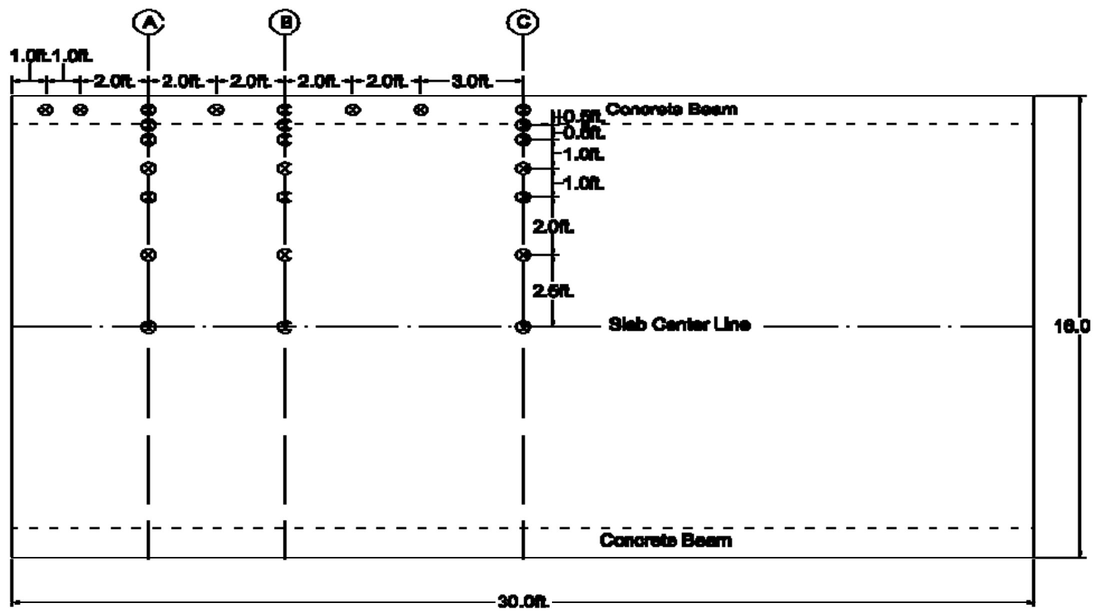

Figure 3: Plan view of the beam-slab under evaluation showing the considered location of the load drops

Evaluation Results for Fixed-End Support Condition

The following tables summarize the results of the load drop evaluations considering that the beams and slab supports are fixed. Table 2 shows the result of the evaluation when the load drop is along the center line of the beam, i.e. no off-center eccentricity was considered. The results in this table are based on the energy balance approach.

As can be seen in Table 2, for load drop locations close to the support, the energy balance method results in unrealistically low permissible lifted weight. The reason is that the energy absorption capacity of the beam is estimated based on the global beam deflection, without consideration of the local damage. Although the local deformation of concrete due to the local damage can be approximated by using a detailed finite

element analysis, there is no simplified procedure to estimate the dissipated energy due to local damage on deformable target structures. Therefore, the energy absorption capacity is estimated by solely considering the global beam deflection.
The results of the evaluation using the dynamic force approach are shown in Table 3. The equivalent dynamic forces are obtained based on the penetration of the load in concrete obtained from Equation (1).

As can be seen, the permissible weights obtained based on the dynamic force approach are larger than the ones that were obtained using the energy balance approach. The reason for these more realistic values is that the dynamic force approach estimates the force by considering the local penetration (damage) of concrete. Therefore, the energy dissipated through local damage is inherently considered in this approach. The results obtained using the dynamic force approach are still considered conservative since this method neglects the global deflection of the beam.

Evaluation Results for Pinned-End Support Condition

The following tables summarize the results of the load drop evaluations considering that the beams and slab supports are pinned. Table 4 shows the result of the evaluation when the load drop is considered along the center line of the beam, i.e. no off-center eccentricity was considered. The results in this table are based on the energy balance approach. The results of the evaluation using the dynamic force approach are shown in Table 5.

Table 2: Summary of the evaluation results for on-center impacts using energy balance approach-fixed supports

Dist. From support (ft)	R_m (kip)	μ	Dominant failure mode	Beam stiffness (kip/in)	d_y (in)	d_l (in)	$E_{capacity}$ (kip.ft)	Allowable lifted weight (kip)
15	170.79	1.3	shear	247.68	0.69	0.08	7.252	**7.252**
12	157.65	1.3	shear	270.20	0.58	0.08	5.608	**5.608**
10	150.16	1.3	shear	330.24	0.45	0.07	4.119	**4.119**
8	143.35	1.3	shear	457.26	0.31	0.06	2.663	**2.663**
6	137.37	1.3	shear	743.05	0.18	0.04	1.460	**1.460**
4	130.97	1.3	shear	1981.46	0.07	0.02	0.466	**0.466**
2	120.75	1.3	shear	7430.47	0.02	0.01	0.083	**0.083**
1	109.58	1.3	shear	19814.57	0.01	0.01	0.010	**0.010**

Table 3: Summary of the evaluation results for on-center impacts using dynamic force approach-fixed supports

Dist. From support (ft)	DLF (*)	Penetration depth (in)	R_m-self weight (kip)	Allowable lifted weight (kip)
15	2.00	7.945	137.410	**90.981**
12	2.00	7.186	124.280	**74.421**
10	2.00	6.752	116.780	**65.714**
8	2.00	6.359	109.970	**58.272**

6	2.00	6.013	104.001	**52.116**
4	2.00	5.643	97.590	**45.891**
2	2.00	5.052	87.370	**36.783**
1	2.00	4.406	76.210	**27.984**

(*) Conservatively, the maximum DLF of 2.0 for a rectangular pulse is considered.

Table 4: Summary of the evaluation results for on-center impacts using energy balance approach-pinned supports

Dist. From support (ft)	R_m (kip)	μ	Dominant failure mode	Beam stiffness (kip/in)	d_y (in)	d_1 (in)	$E_{capacity}$ (kip.ft)	Allowable lifted weight (kip)
15	162.23	10	flexure	108.08	1.50	0.19	191.484	**191.484**
12	160.66	1.3	shear	116.56	1.38	0.18	13.525	**13.525**
10	153.81	1.3	shear	135.10	1.14	0.17	10.592	**10.592**
8	146.39	1.3	shear	169.84	0.86	0.15	7.496	**7.496**
6	137.62	1.3	shear	247.68	0.56	0.12	4.398	**4.398**
4	126.38	1.3	shear	457.26	0.28	0.09	1.865	**1.865**
2	111.51	1.3	shear	1486.09	0.08	0.05	0.335	**0.335**
1	101.38	1.3	shear	5944.37	0.02	0.02	0.020	**0.020**

Table 5: Summary of the evaluation results for on-center impacts using dynamic force approach-pinned supports

Dist. From support (ft)	DLF (*)	Penetration depth (in)	R_m-self weight (kip)	Allowable lifted weight (kip)
15	2.00	7.451	128.860	**80.009**
12	2.00	7.360	127.280	**78.061**
10	2.00	6.964	120.440	**69.894**
8	2.00	6.535	113.010	**61.540**
6	2.00	6.028	104.250	**52.366**
4	2.00	5.378	93.011	**41.683**
2	2.00	4.518	78.140	**29.421**
1	2.00	3.932	68.000	**22.281**

(*) Conservatively, the maximum DLF of 2.0 for a rectangular pulse is considered.

Comparison of the results shown in Table 4 with Table 2 shows that the energy balance approach results in higher permissible lifted weight over a simply supported beam than a fixed-end beam. This is expected since a simply supported beam has a lower stiffness and a larger yield displacement. Therefore, the area under the force-displacement curve of a simply supported beam is larger than a fixed beam. Additionally, the results shown in Tables 4 and 5 indicate that the energy balance approach resulted in a larger permissible lifted weight at the center of the beam than the dynamic force approach. Further evaluation of the beam at the center reveals that the failure of the simply supported beam at the center is governed by flexure whereas the failures at all other locations are governed by shear. When the failure is governed by flexure, an allowable ductility of 10 can be used, which is significantly larger than the allowable ductility of 1.3 for shear failure. Therefore, the area under the force-displacement curve of a flexure dominant beam is significantly larger. In other words, the majority of the work done by the impact force for a flexure dominant structure is due to the global deflection rather than the local penetration/crushing damage. Therefore, where the failure mode of the beam is governed by flexure, the energy balance approach results in a higher permissible lifted weight, and is preferred to be used.

Evaluation of the Beam for Off-Center Load Drop Impact

At first glance, the drop on the centerline of the beam appears to be the worst accidental load drop postulation scenario since all the impact energy is transferred directly to the beam. However, since the off-center impacts can produce torsion, which further reduces the capacity of the beam, the off-center impacts may need to be evaluated as well. Since such evaluations requires consideration of both torsion and shear simultaneously, the evaluation of the capacity of the beam, R_m becomes an iterative process. The procedure is described below:

1- Make an initial guess for the shear capacity of the beam R_{m_shear}.
2- Calculate the induced maximum shear and torsion resulting from R_m.
3- Calculate the required shear reinforcement area without consideration of torsion, i.e. based on vertical shear only, per applicable design code (For example, Equation (11-16) of ACI 349 (2006)).
4- Calculate the required shear reinforcement area without consideration of vertical shear, i.e. based on the torsion only, per applicable design code (for example, Equation (11-21) of ACI 349 (2006)).
5- Sum the shear reinforcement areas obtained in steps 3 and 4. If this value is different from the available shear reinforcement area, adjust the value of R_{m_shear}.
6- Repeat steps 2 through 5 until the required shear reinforcement area matches with the available shear reinforcement area.
7- Based on the required torsional shear reinforcement calculated in step 4, calculate the required area of longitudinal reinforcement to resist torsion, per applicable design code (for example, Equation (11-22) of ACI 349 (2006)) and use the remaining longitudinal rebar area to calculate the moment capacity of the beam, $R_{m\_flexure}$.
8- Declare the minimum value of $R_{m\_flexure}$ and R_{m_shear} as the total capacity of the beam, R_m.

Using the procedure above, the capacity of the beam, R_m is calculated for off-center impact on locations along the lines A, B and C as shown in Figure 3. The results are shown in Figure 4.

It should be noted that the shear reinforcement spacing of 10 inches used for the model in this study is based on the minimum required spacing of *d/2* where *d* is the effective depth of the beam (see Section 11.5.5.1 of ACI 349 (2006)). Therefore, the shear and torsion capacity are expected to be somewhat less than a typical reinforced concrete beam where smaller stirrup spacing are used. However, results in Figure 4 show that even though the shear reinforcement is somewhat minimal, the torsion is not governing, and the capacity of the beam can be obtained by considering the impact load directly applied on the centerline of the beam. Although these results cannot be generalized to all beams of different sizes and reinforcements, the results are expected to be somewhat similar for most beams.

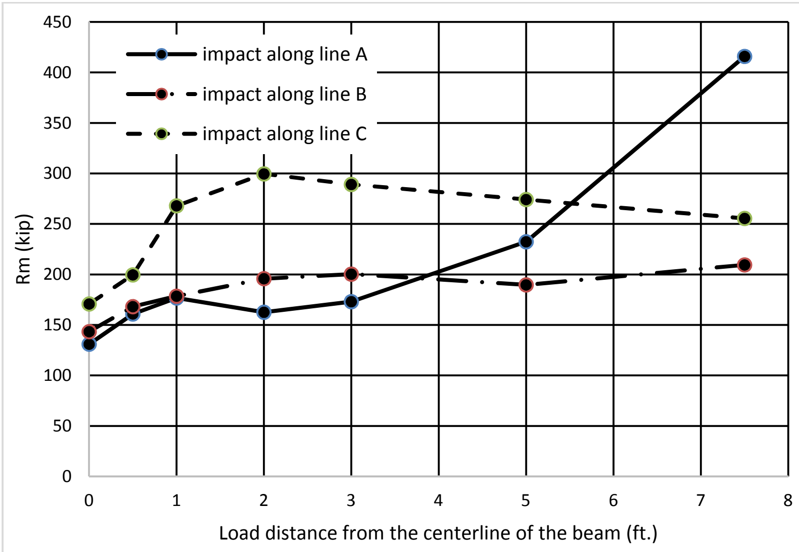

Figure 4: Capacity of the beam for off-center impacts

CONCLUSION

This study compares the typical approaches used in simplified calculations for evaluation of the load drop capacity of structural elements used in US nuclear power plants. The emphasis is given to the criteria given in NUREG-0612 (1980) which imposes some limitations on the methodologies that can be used for capacity evaluation of nuclear power plant structures against accidental load drops. Two methodologies are discusses in detail, namely, the energy balance approach and the dynamic force approach. Both approaches were used to evaluate the load drop capacity of a concrete beam supporting a one-way slab. The following results were observed based on the case study provided in this article:

1- The energy balance approach may result in unrealistically low load drop capacity in a concrete beam with low ductility, and for load drops at locations close to the supports. The low ductility can be due to the dominant mode of failure being shear rather than flexure, or due to the type of support conditions. In these cases, the methodology based on force approach should be used.
2- The force approach discussed in this article will result in more realistic load drop capacity of the beam. However, as discussed earlier, the load drop capacity obtained using dynamic force approach can still be considered conservative since the forcing function does not take credit for the global deflection of the structural element under consideration.
3- When the mode of failure is dominated by flexure, due to the fact that a significantly higher permissible ductility can be used for flexural mode of failure, the energy balance approach will typically result in higher capacity than the

dynamic force approach. Therefore, use of the energy balance approach for these cases is recommended.

4- The methodology for evaluation of the structure for off-center load drops was explained in this article. For this case study, it was shown that the allowable lifted weight obtained based on off-center impacts are more than the allowable lifted weight obtained based on the impacts on centerline of the beam.

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