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IMPACT RESPONSE OF FALLING OBJECT PROTECTIVE STRUCTURES

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Abstract: This paper examines the effects of falling objects impacting on protective structures in the mining industry. The impact problem is defined in terms of the equality between impact energy and work energy dissipation of the structure. To obtain realistic results from the mathematical structural model, the assumption is made that the impact energy is distributed to all members that experience deformation from the impact. The distribution of the impact energy to the structural members is taken as proportional to the work done by the members at impact. The problems encountered in quantifying the magnitude of the impact energy and the formulation of a design criteria are discussed. Numerical examples are presented to illustrate the mathematical procedure to estimate both elastic and rigid plastic response of the structural members impacted by a falling object.

1 INTRODUCTION

In the mining industry workers are required to perform work in places where there is a risk that falling objects, such as rocks, may enter the work area. Therefore, for the protection of the miners, overhead protective structures have to be provided. Protective structures, or FOPS, are e.g. bulk heads in shafts, canopies on conveyances and work stages and protective canopies on mobile equipment.
The practical design of FOPS is difficult because the falling object parameters are subject to assumptions and limited information. Recently (Haydl 2016, 2018) has discussed some topics on the design of FOPS such as falling object parameters, design criteria and rock impact fragmentation.
The present paper presents a simple method to estimate the response of protective steel structures to falling objects. The analysis procedure is based on a balance between the impact energy of the falling object and the energy absorbed by the structure. It is observed that when only the impacted member is considered, an upper bound conservative estimate of the structural response is obtained. This leads to overly heavy protective structures. A more realistic result is obtained if all members that deflect on impact are included in the analysis. The procedure on how to estimate these responses is detailed in this paper. Both elastic and rigid plastic structural responses are investigated. Examples are presented to illustrate the methodology.

2 IMPACT ON SINGLE STRUCTURAL MEMBER

The energy balance between the falling object and the structural member can be expresses as

[1] $\frac{1}{2} P D = \frac{1}{2} m v^2$, or (= W H)

In this equation the left side represents the energy absorbed by the structural member and the right side is the impact energy of the falling object.

Here the parameters are defined as
P = the impact force on the structural member
D = the deflection of the member at the impact location
m = W/g, the mass of the falling object, g = 9.81 meters/sec^2
v = the velocity of the falling object at impact, $v^2 = 2\ g\ H$
W = the weight of the falling object
H = the free fall distance

The solution of "Eq.1" is obtained at the intersection of the structural response D = f (P) and the impact energy ½ P D. This is illustrated in Fig.1.

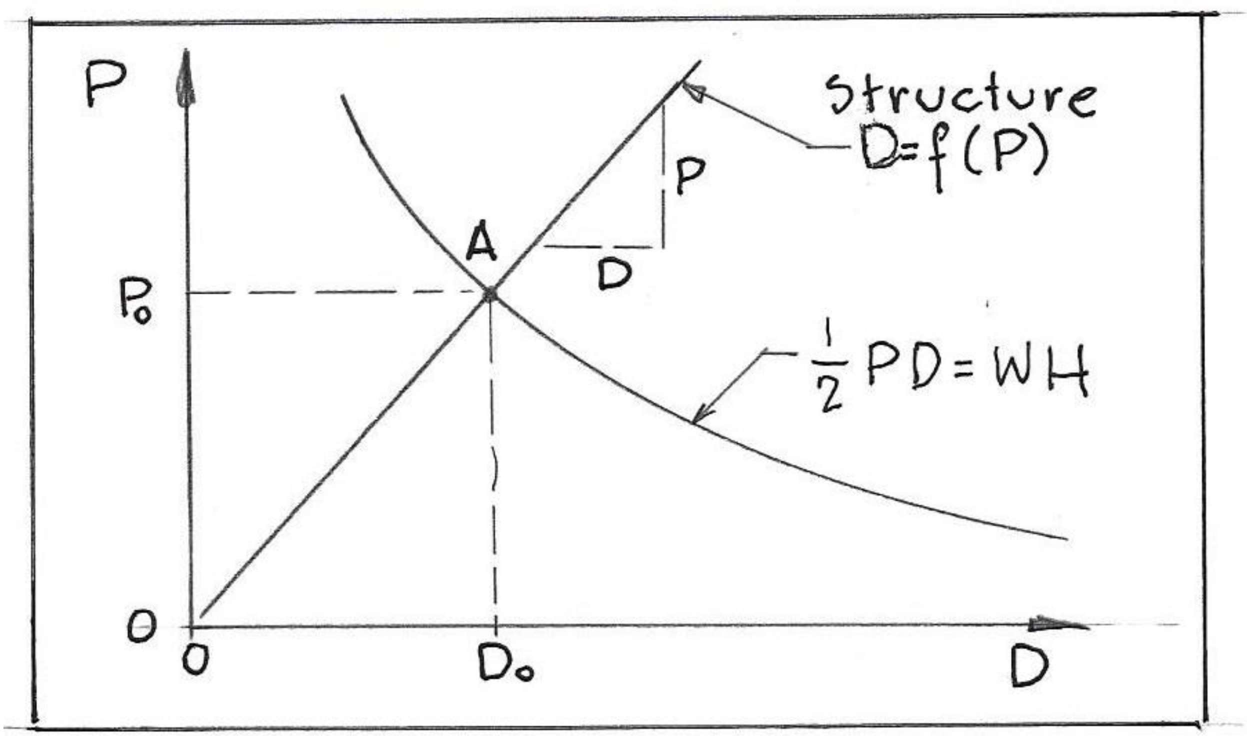

Fig. 1: Impact load P vs. deflection D for single member impact

Example 1: Consider a W250x67 steel beam, simply supported span of 3.28 meters, is impacted by a 0.455 KN rock falling from 15.2 meters height.
The impact energy is

[2] W H = 0.455 x15.2 = 6.92 KN m

The deflection at mid span is

[3] $D = P\ L^3 / 48\ E\ I$

Substituting "Eq.2" and "Eq.3" into "Eq.1" results in

[4] $\frac{1}{2} P^2 L^3 / 48 E I = 6.92$ KN m

The solution for the impact force $P_0 = 696$ KN,"Eq.4" and the elastic deflection $D_0 = 20$ mm,"Eq.3".

3 IMPACT ON STRUCTURES WITH MULTIPLE MEMBERS

"Eq.1" can be expanded to include all structural members of the FOPS that are connected to the impacted member and are experiencing deflections from the impact.
The elastic response of a multi member structure is evaluated from

[5] $\sum \frac{1}{2} P_i D_i = \frac{1}{2} m v^2$ or (W H)

here the subscript "i" denotes the number of structural members that will see deflections from the impact. Because the impact energy is absorbed by multiple members, it is necessary to assign a portion of the impact energy to each individual beam. This is done with the following procedure.

a. Assume an arbitrary impact load applied at the impact point.
b. Obtain the maximum elastic deflection d_i for each member.
c. Calculate the value of the member force f_i that resulted in the deflection d_i, considering the boundary conditions, supports and effective cross section of each beam.
d. Calculate the work done by each member as $w_i = f_i d_i$
e. Define the distribution coefficient $k_i = f_i d_i / \sum f_i d_i$, expressing the relative distribution of the impact energy to the members.
f. We shall apply this coefficient to the impact energy W H, denoting the distribution to each beam proportional to the work done by each beam.
g. "Eq.5" can be rewritten as

[6] $\frac{1}{2} P_i D_i = k_i W H$, expresses the energy balance for an individual beam.

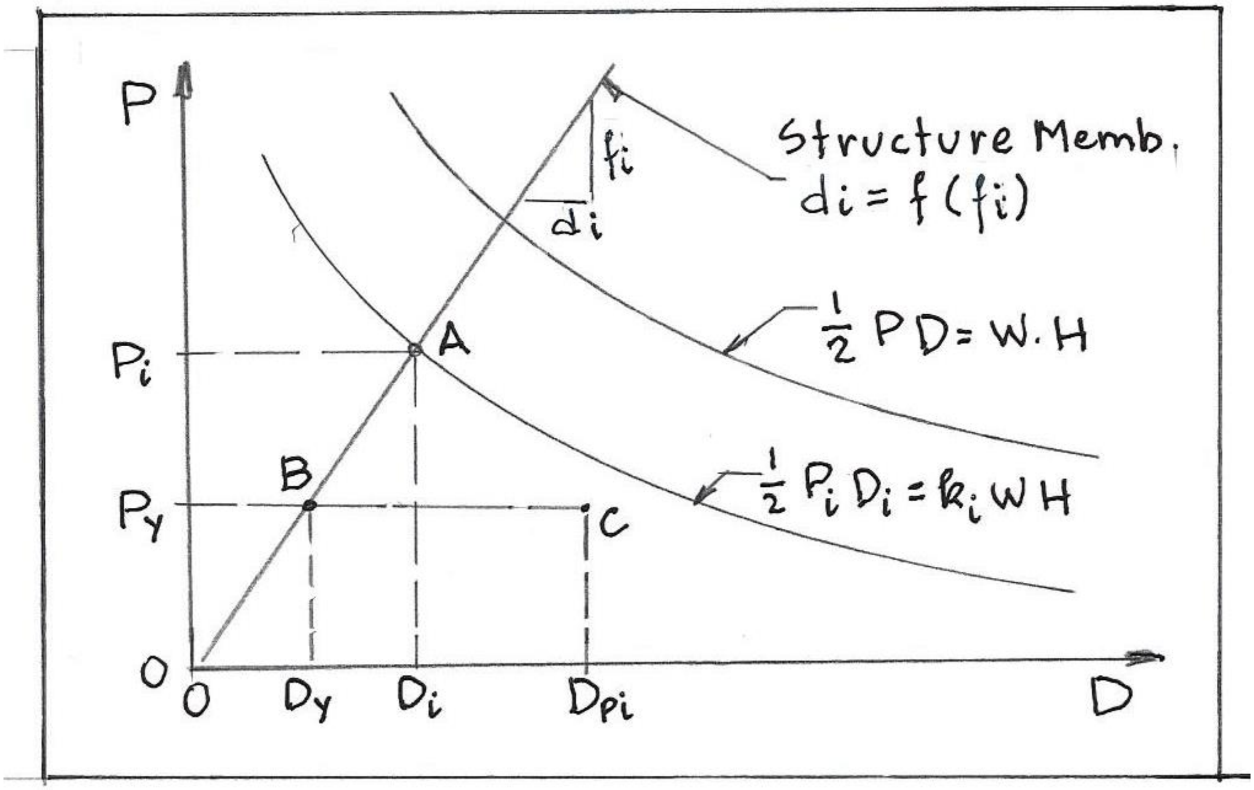

Fig.2 Impact load P_i vs deflection D_i for a single member of a multimember FOPS.

Fig. 2 shows the solution of equation "Eq.6" at the intersection of member response and assigned impact energy, point A, i. e. the impact load P_i and the corresponding elastic deflection D_i for the individual beam. A similar graph can be constructed for each beam in the structure.
By using the impact load P_i one can now calculate maximum stresses in the beam. If it is found that the stresses exceed the yield point for the material, the following procedure can be used to estimate the rigid plastic deformations. In Fig.2 the elastic energy assigned to a beam is equal to the area of the triangle 0 A D_i . This "elastic" energy must equal the "inelastic" energy which is equal to the area 0 B C D_{pi} , namely

[7] $½ P_i D_i = P_y (D_{pi} - 1/2\, D_y)$

This equality is solved for the inelastic deflection D_{pi} .

Example 2:
The protective structure shown in Fig.3 consists of a grid of steel beams (W200x36) that is covered with a plate (t=13 mm) and supported at the corners by columns. It is assumed that a rock impacts the FOPS at its center with an impact energy of 13.57 KN m.

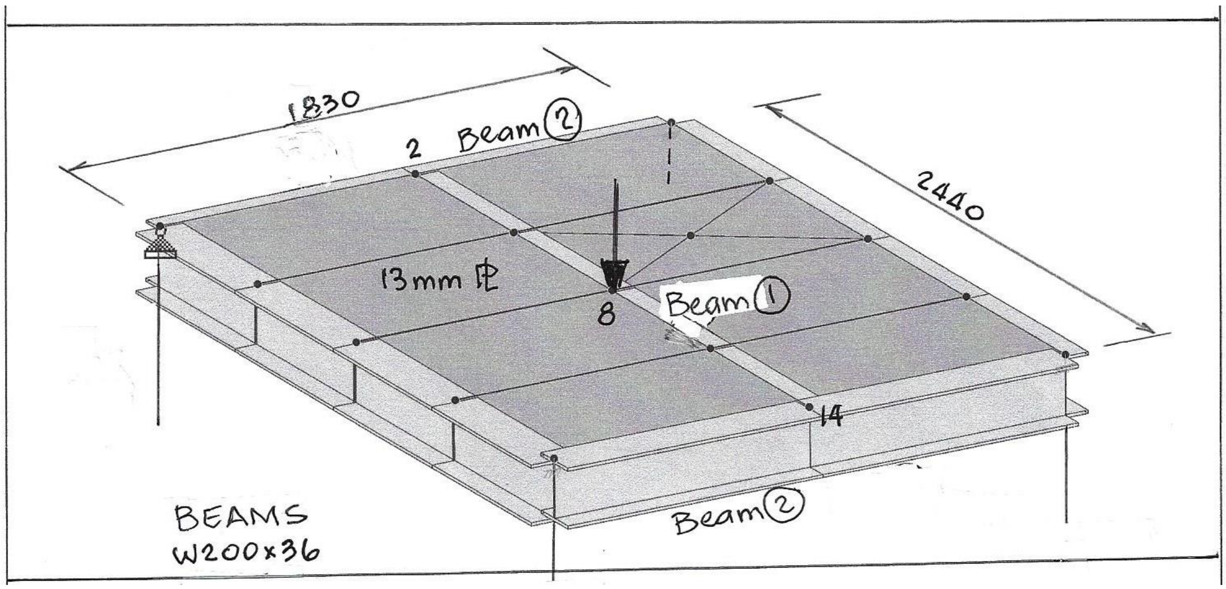

Fig. 3 Geometry of multi member FOPS (Example 3)

The task at hand is to estimate the deformations of the structural members as a result of the impact. We shall illustrate the procedure for beam 1 only in detail, but point out that this method is similar for other members.
The steps in the analysis are

a) Assume an arbitrary force of 300 KN applied at node 8 of the FOPS. The resulting deflections are

Node	deflection
2	$d_2 = 3.1$ mm
8	$d_1 = 11.66$ mm
14	$d_2 = 3.1$ mm

b) Estimate the force f_i that resulted in these deflections

Beam 1: The cross section is the W200 + plate
The effective width of the plate is

$w_1 = 1.7 \times 13 \times (E/F_y)^{0.5} = 625$ mm, here E =200KN/mm^2 , F_y =250 MPa
resulting in $I_1 = 68.3 \times 10^6$ mm^4 , $S_1 = 403.1 \times 10^3$ mm^3

the force f_1 that resulted in the deflection $d_1 = 8.56$ mm (net deflection) is found to be

$f_1 = (11.66 - 3.1)\ 48\ E\ I_1 / (L_{1)})^3 = 386$ KN
Note that beam 1 undergoes a rigid body motion of 3.1 mm
The work done is $w_1 = 0.00856 \times 386 = 3.3$ KN m

Beam 2: Similarly we obtain

$w_2 = 312$ mm, $I_2 = 59.4 \times 10^6$ mm^4 , $S_2 = 393 \times 10^3$
$f_2 = 3.1 \times 48\ E\ I_2 / (L_2)^3 = 288$ KN
the work done is $w_2 = 0.0031 \times 288 = 0.89$ KN m

c) Estimate the impact energy portion assigned to each beam. By the definition in section 3, the energy distribution coefficient k_i is

Beam 1: $k_1 = w_1 / \sum w_i$ = 3.3/(3.3 + 2 x 0.89) = 0.65 , therefore the impact energy is
½ $P_1 D_1$ = 0.65 x 13.57 = 8.82 KN m

Beam 2: $k_2 = w_2 / \sum w_i$ = 0.89/(3.3 + 2 x 0.89) = 0.175, and the impact energy is
½ $P_2 D_2$ = 0.175 x 13.57 = 2.37 KN m

d) The response of beam 1 is shown in Fig. 4. The assigned impact energy is 8.82 KN m.
It can readily be verified that the yield load (max. fiber stress at yield) of the beam is F_y = 165 KN, Which is below the elastic load of 895 KN, i.e. the beam will see large inelastic deflections.
The estimate of the inelastic deflection is obtained from Fig.4 by setting the elastic impact energy (area 0AB) equal to the inelastic impact energy (area 0CDE).
½ $P_1 D_1$ = 8820 KN mm = 165 (D_{p1} – ½ x 3.6)
Solving for D_{p1} = 55.3 mm as the maximum inelastic deflection of beam 1

e) The estimate of the maximum deflection of beam 2 follows the same procedure and results in an inelastic deflection of D_{y2} = 12.2 mm.

Note that the total inelastic deflection of the two beams entering the work space is
D = 55.3 + 12.2 = 67.3 mm.

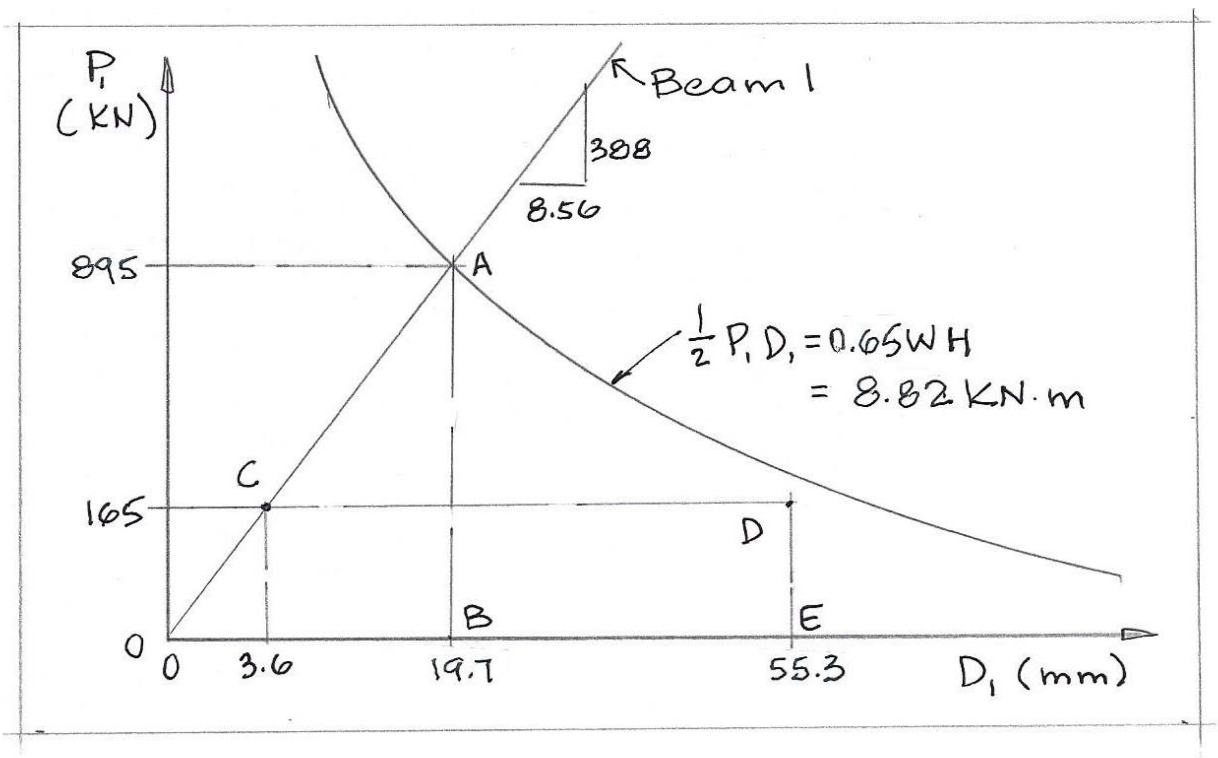

Fig. 4 Impact load P_1 vs. deflection D_1 for beam 1 of example 2.

4 DESIGN CRITERIA

Published design criteria,(SAE 1981, ISO 2005) are available but do not strictly apply to the present problems. For mining applications there are two areas of importance to be considered.

The first is that of establishing the value of the maximum impact energy the FOPS should be designed for. This is best determined with consulting with the geotechnical engineer at the specific mine site, who may have experience with rock falls. The information of interest is not only the mass and drop height of the falling rock, but also its density and physical shape. This bears directly on the theoretical analysis because rock fragmentation and high velocity impact assumptions will change the results.

The second consideration is the setting of a design limit on the maximum deflections of the FOPS. It is desirable to limit deflections in case the FOPS is designed for multiple use. Limit on deflections must prevent deformations of structural members to enter the work space.

It should be evident that the specification of a general design criteria is difficult. The large number of parameters to be considered in each design will require that the design assumptions have to be site specific. In order to gain some confidence, that a design has a high probability to protect against falling rocks, physical testing of a FOPS is important.

In the end, however, there is no guarantee that the design assumptions will match the real loading on the FOPS.

5 SUMMARY

This paper presents a simple method to estimate the response of a structure when impacted by a falling object. The mathematical model is based on the energy balance of impact energy and work done by the structure. It is evident that a reliable design of a FOPS is a very difficult task, since the values of some design parameters are hard to define. One can develop mathematical models and methods of analysis for FOPS, but the uncertainty of the design parameters can make for questionable results. Therefore, testing of full scale FOPS is necessary to confirm their safety.

6 REFERENCES

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