Reliability Index of Simply Supported Beam Based on HL Method

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Abstract

In this paper, reliability of simply supported I-beam is studied under point load at the mid-point of span. Reliability index has been obtained by using Hasofer-Lind method. In the analysis, yield strength of material, depth of the section and load are considered as basic random variables and those are assumed to follow normal distribution. Non-linear limit state surface function has been considered. Derived design point in each case and found the reliability.

Keywords: Reliability, I-beam, reliability index, non-linear limit state function, stress, strength, load, normal distribution.

Notations

R	Reliability
β, β_1, β_2	Reliability indices

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C	Strength of the beam
S	Stress of the beam
M	Marginal function/Failure function
p_f	Probability of failure
D	Design point or Check point
q	The minimum distance from origin to failure surface
z^*	Coordinates of design point
p	Point load
g	Failure surface
d	Depth of the beam
f_s	Strength of the material
t_w	Thickness of the web
Φ	Cumulative standard normal distribution function
α_i	Direction cosines along axes in the normalized co-ordinate system
X_i	Basic variables
Z_i	Coordinates in the normalized coordinate system
μ_{f_s}	Mean yield strength of material
μ_p	Mean of load
σ_{f_s}	Standard deviation of material yield strength
σ_p	Standard deviation of load
μ_M	Mean of M
σ_M	Standard deviation of M
δ_C	Coefficient of variation of C
δ_S	Coefficient of variation of S

1 Introduction

The goal of a structural designer is to plan a design for a safe and economical structure such that the structure should fulfil its intended purpose. A structural design is developed by calculating internal forces and moments on components of the structure. In engineering design, reliability is the probability that the design meets certain demands under given conditions. For stability of a structure, it should be designed such that it satisfies demands towards loads on the structure. The resistance capacity (C) of a structure and stress of the beam (S) then structure is safe if C>S, mathematically expressed as C-S>0. M=C-S is known as limit state function or failure function. M is a function of n basic design variables x_1, $x_2 \ldots$ x_n. The function divides the design space into safe zone and unsafe zone with respect to C and S. For safe region M>0 and for unsafe region M<0. Since the resistance of structural element and loads acting on it are a function of several variables, most of the variables are random in nature. Hence probabilistic approach is suitable in the design of a structure. Structural safety deals with violation of ultimate or serviceability limit states of the structure.

Reliability is a branch of structural engineering and is the probabilistic assessment and analysis of design variables. Reliability index β is the measure of probability of failure of an element or structure. It was defined by Cornell [18] as $\beta = \frac{\mu_M}{\sigma_M}$ where M be the limit state function. If the design variables are normally distributed then $\beta = -\Phi^{-1}(p_f)$, where Φ is the cumulative standard normal distribution function.

Syed Hooman Gasemi and Andrezej S Nowak [7] calculated the reliability indices for segments of circular tunnel and designed as per manual report of tunnel. Design codes have been derived to conform safety level of the structure. Resistance and load factor design approaches were used, which measures the safety of the structure in terms of reliability indices. Karthik C B et al. [8] analysed reliability for structures made by frames. Loads and strength assumed to follow required distribution. Limit state functions for bending, shear and deflection are considered. Performance functions are studied by Rackwitz algorithm and reliability index was derived using a Matlab programme. O J Aladegboye et al. [9] Used First Order Reliability Method (FORM) for the analysis of simply supported concrete beam. Depth, length and concrete strength are considered as parameters. The result of the model clears that formal deterministic way of calculating safety factor failed to put into consideration of uncertainties in depth, length and strength. E Bastidas and A.H. Soubra [10] were made reliability analysis by taking example for comparison of the Second and First Order Reliability Methods. In the analysis, limit state function is approximated by Taylor series approximation at mean values of design variables. Christopher D. Eamon and Elinjensen [11] were estimated reliability for 0–5 hours of fire exposer using Monte Carlo Simulation Method and cleared that reliability decreases non-linearly with function of time. A.Satyanarayana et al. [19] derived reliability of simply supported beam under uniformly distributed load. Span, width and depth of the beam are considered to follow normal distribution. Bending strength, loads, tolerance of depth of the beam, width of the beam taken into account in the analysis. Reliability analysis has been done with respect to material strength, load, tolerance of depth.

In this article, simply supported I-beam under point load at mid-point of span is taken for the analysis of reliability. Strength of the material, depth of the section and load are assumed to follow normal distribution. Non-linear limit state function is taken for the analysis and derived design points as per required reliability.

This work may be useful in designing simply supported I-beams which are used in structures.

2 Methodology

Cornel reliability index β is unique for equivalent linear failure functions of basic variables. If the safety margin M of a function is not a linear function then for its equivalent non-linear functions there may be different values for the Cornel reliability index β.

$M = C - S$ where C, S are un-correlated then the reliability index by Cornel for the failure function is

$$\beta_1 = \frac{\mu_M}{\sigma_M} = \frac{\mu_C - \mu_S}{\sqrt{\sigma_C^2 + \sigma_S^2}}$$

Consider the equivalent failure function, $M = ln\frac{C}{S} = ln\ C - ln\ S$, then the Cornel reliability index, $\beta_2 = \frac{\mu_{\ln(\frac{C}{S})}}{\sigma_{\ln(\frac{C}{S})}}$.

If the linearization of the safety margin, $M = ln\ C - ln\ S$ is done about μ_{C} and μ_{S} then

$$\beta_2 = \frac{ln\left(\frac{\mu_{\mathrm{C}}}{\mu_{\mathrm{S}}}\right)}{\sqrt{\delta_C^2 + \delta_S^2}}.$$

It is clear that β_1 and β_2 are not equal. Hence, in the case of non-linear failure functions, the Cornel's reliability index is not invariant.

There are disadvantages also in the First Order Second Moment Method (FOSM). In the linearization process of non-linear failure function about mean values, there are truncation errors take place by neglecting higher order terms in the Taylor's series approximation. In many structural engineering problems generally the mean point is away from the failure space. Thus there are unacceptable errors present in the process.

2.1 Model Assumptions

(i) Limit state function is taken as a function of load acting on the beam, strength of the material, depth of the beam and thickness of web.
(ii) All variables are to be considered to follow normal distribution.

2.2 Model Description

Hasofer and Lind Method

Let f be a failure surface function of independent basic variables $X_1, X_2 \ldots . X_n$. The basic variables are transformed using the relation

$$Z_i = \frac{X_i - \mu_{X\,i}}{\sigma_{X_i}}, \quad i = 1, 2 \ldots . n$$

where $\mu_{X\,i}$ and $\sigma_{X\,i}$ be the mean and the standard deviation of X_i. Here the Z co-ordinate system is said to be normalized co-ordinate system. The failure surface function is written in the normalized co-ordinate system. Reliability index was defined by Hasofer and Lind, which is the minimum distance from origin to the failure surface in the Z co-ordinate system. The point D where the perpendicular meets the surface is called check point or design point.

In the method, the failure surface is approximated by a hyper tangent plane to the surface. Safety measure obtained in the method is invariant for equivalent failure functions. In case of failure function is linear, the reliability index $\beta = \frac{\mu_M}{\sigma_M}$ of Cornell, which agrees with the value β defined by Hasofer and Lind. The failure surface divides the design space into two regions, safe region and unsafe region. If the failure surface is concave and this side having

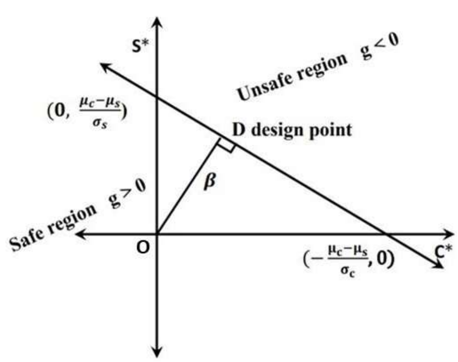

Figure 1 Design point.

origin then the approximation for D will be on safer side, otherwise it will be on unsafe side. Let $f(X_1,\ X_2 \ldots . X_n)$ be a nonlinear limit state function in the original variable space and $g(Z_1, Z_2, \ldots . Z_n)$ be the non-linear limit state function in the normalized co-ordinate space.

Let D be the point $z^*(z_1^*, z_2^*, \ldots . z_n^*)$ and the distance q from a point $z(z_1, z_2, \ldots . z_n)$ on the failure surface to the origin such that $g(z_1, z_2, \ldots . z_n) = 0$.

The problem reduces to finding of minimum values for q, where $q = \sqrt{z_1^2 + z_2^2 + \cdots z_n^2} = \sqrt{z^t z}$ and q will be minimized subject to the condition

$$g(z_1, z_2, \ldots . z_n) = 0.$$

Consider the Lagrange function $F = q + kg(z) = \sqrt{z^t z} + kg(z)$.

For minimization $\frac{\partial F}{\partial z_i} = 0$, where $i = 1, 2 \ldots n$ and $\frac{\partial F}{\partial k} = 0$.

Implies $\frac{z_i}{\sqrt{z^t z}} + k\frac{\partial g}{\partial z_i} = 0$ and $g(z_1, z_2, \ldots . z_n) = 0$.

Then $\frac{z}{q} + kG = 0$, where $G = (\frac{\partial g}{\partial z_1}, \frac{\partial g}{\partial z_2} \ldots . \frac{\partial g}{\partial z_n})$ is called gradient vector.

Therefore $z = -kqG$.

Let

$$z^* = -k^* q^* G^* \tag{1}$$

where q^* be the minimum distance from the origin to the limit state surface.

Since $q^* = \sqrt{z^{*t} z^*} = \sqrt{(-k^* q^* G^*)^t (-k^* q^* G^*)} = k^* q^* \sqrt{G^{*t} G^*}$.

Therefore $k^* = (G^{*t} G^*)^{-\frac{1}{2}}$.

Using Equation (1), the minimum distance $q^* = \frac{-z^* G^{*t}}{\sqrt{G^{*t} G^*}}$.

Therefore reliability index

$$\beta = \frac{-z^* G^{*t}}{\sqrt{G^{*t} G^*}} \tag{2}$$

$$= \frac{-\sum_{i=1}^{n} z_i^* (\frac{\partial g}{\partial z_i})_*}{\left[\sum_{i=1}^{n} \left(\frac{\partial g}{\partial z_i}\right)_*^2\right]^{\frac{1}{2}}}$$

From Equation (2), it is known that $z^* = \frac{-\beta^* G^*}{\sqrt{G^{*t} G^*}}$ and $z_i^* = \beta \alpha_i$, where $\alpha_i = \frac{-(\frac{\partial g}{\partial z_i})}{\sqrt{G^{*t} G^*}}$, $\sum_{i=1}^{n} \alpha_i^2 = 1$, and α_i are the direction cosines along axes in the normalized co-ordinate system.

Iterative method can be used to find minimum value for β for a non-linear failure surface function.

3 Calculation of Reliability

Consider the simply supported I-beam AB under limit state of shear and the beam is subjected to the point load p at midpoint of span. Design variables are normally distributed. Let $(\mu_p, \mu_{f_s}, \mu_d)$ and $(\sigma_p, \sigma_{f_s}, \sigma_d)$ be the vector of mean and standard deviations of load p, shear strength f_s of the material and depth d of the beam respectively. Assume that t_w is thickness of the web and deterministic variable such that

$$\frac{d}{t_w} = 40. \tag{3}$$

Maximum shear force $= \frac{p}{2}$ and resistance to the shear $= f_s t_w d$.

The beam fails if $f_s t_w d \leq \frac{p}{2}$.

Therefore the equation of failure surface is given by

$$f = f_s t_w d - \frac{p}{2} = 0. \tag{4}$$

Using the Equation (3), the failure surface function (4) in the normalized co-ordinate system is given by

$$g = \frac{\mu_d}{40}\left(\sigma_{f_s} z_1 \sigma_d z_2 + \sigma_{f_s} z_1 \mu_d + \mu_{f_s}\sigma_d z_2 + \mu_{f_s}\mu_d\right) - \frac{\sigma_p z_3}{2} - \frac{\mu_p}{2} = 0. \tag{5}$$

Where $z_1 = \frac{f_s - \mu_{f_s}}{\sigma_{f_s}}$, $z_2 = \frac{d-\mu_d}{\sigma_d}$, $z_3 = \frac{p-\mu_p}{\sigma_p}$.

Since

$$Z_1 = \beta\alpha_1, \quad Z_2 = \beta\alpha_2 \quad \text{and} \quad Z_3 = \beta\alpha_3 \tag{6}$$

Therefore the relation obtained from Equations (5) and (6) is

$$\beta = \frac{\frac{-\mu_d}{40}\left(\mu_{f_s}\mu_d\right) + \frac{\mu_p}{2}}{\frac{\mu_d}{40}\left(\sigma_{f_s}\beta\alpha_1\sigma_d\alpha_2 + \sigma_{f_s}\alpha_1\mu_d + \mu_{f_s}\sigma_d\alpha_2 - \frac{\sigma_p\alpha_3}{2}\right)} \tag{7}$$

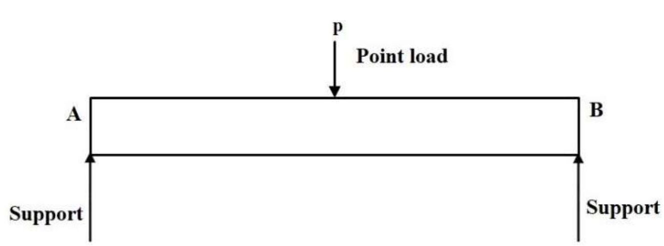

Figure 2 Simply supported beam subjected to the point load at midpoint of span.

Considering initial values for β and α_i as $\beta = 6$, $\alpha_1 = -0.58$, $\alpha_2 = -0.58$, $\alpha_3 = 0.58$ for the iterative method. Matlab is used for the calculations.

4 Numerical Results

4.1 Mean Load Vs Reliability

From the Table 2 it is noticed that reliability was computed for different values of mean load on the beam and observed that the increment in load from 2000N to 7000N at standard deviation 1000N effects the decrease of reliability index from 3.721 to 0.136 and reliability from 0.9999 to 0.554089.

Table 3 shows that, if mean point load decreases from 2000N to 7000N at standard deviation 800N then reliability changes from 0.999954 to 0.559618 and reliability index changes from 4.179 to 0.156. Mean shear strength of material Vs Reliability.

As per the Table 4 material strength changes from 115 N/mm^2 to 45 N/mm^2 reliability index decreases from 3.815 to 0.075 and reliability of the structural member decreases from 0.999932 to 0.529893.

It is evident from the Table 5 that material strength changes from 115 N/mm^2 to 50 N/mm^2 causes decrease in the reliability from 0.999961 to o.655422 and reliability index from 3.958 to 0.4.

Table 2 Simply supported beam subjected to the point load at midpoint of span-1

$\sigma_p = 1000N, \mu_{f_s} = 90\ N/mm^2, \sigma_{f_s} = 10\ N/mm^2,$
$\mu_d = 40\ mm, \sigma_d = 4\ mm, t_w = 1.25\ mm.$

μ_p	f_s	d	p	β	p_f	R
2000	108.8	46.4	4791.3	3.721	0.000099	0.999900
2500	107.0	45.8	4989.6	3.348	0.000407	0.999593
3000	105.3	45.3	5194.8	2.978	0.001451	0.998549
3500	103.5	44.7	5407.1	2.611	0.004514	0.995486
4000	101.7	44.1	5626.6	2.247	0.012320	0.987680
4500	99.9	43.5	5853.2	1.887	0.029580	0.970419
5000	98.1	42.8	6087.0	1.530	0.063009	0.936992
5500	96.3	42.2	6327.9	1.177	0.119600	0.880402
6000	94.4	41.6	6576.0	0.826	0.204400	0.795598
6500	92.6	40.9	6831.1	0.479	0.316000	0.684031
7000	90.7	40.3	7093.2	0.136	0.445911	0.554089

Table 3 Simply supported beam subjected to the point load at midpoint of span-2

$\sigma_p = 800N, \mu_{f_s} = 90\ N/mm^2, \sigma_{f_s} = 10\ N/mm^2,$
$\mu_d = 40\ mm, \sigma_d = 4\ mm, t_w = 1.25\ mm.$

μ_p	f_s	d	p	β	p_f	R
2000	113.3	47.7	4308.7	4.179	0.000015	0.999954
2500	111.0	47.1	4544.2	3.750	0.000084	0.999912
3000	108.8	46.4	4789.0	3.327	0.000439	0.999561
3500	106.6	45.7	5043.1	2.910	0.001807	0.998193
4000	104.3	44.9	5306.5	2.499	0.006227	0.993773
4500	102.1	44.2	5579.1	2.093	0.018175	0.981826
5000	99.8	43.4	5860.6	1.693	0.045228	0.954773
5500	99.6	42.7	6150.8	1.299	0.096972	0.903028
6000	95.4	41.9	6499.6	0.910	0.181411	0.818589
6500	93.1	41.1	6756.7	0.527	0.299097	0.700903
7000	90.9	40.3	7071.8	0.156	0.440382	0.559618

Table 4 Mean shear strength of material Vs Reliability-1

$\mu_p = 3500N, \sigma_p = 1000N, \sigma_{f_s} = 10\ N/mm^2,$
$\mu_d = 40\ mm, \sigma_d = 4\ mm, t_w = 1.25\ mm.$

μ_{f_s}	f_s	d	p	β	p_f	R
115	132.0	48.4	6188.6	3.815	0.000068	0.999932
110	126.5	47.6	6051.5	3.589	0.000166	0.999834
105	120.9	46.9	5904.3	3.355	0.000397	0.999603
100	115.2	46.1	5747.4	3.114	0.000923	0.999077
95	109.4	45.4	5581.5	2.866	0.002078	0.997922
90	103.5	44.7	5407.1	2.611	0.004514	0.995486
85	97.4	44.0	5225.0	2.350	0.009387	0.990613
80	91.3	43.4	5035.6	2.082	0.018671	0.981329
75	84.4	42.8	4839.7	1.810	0.035148	0.964852
70	78.6	42.2	4637.9	1.532	0.062761	0.937239
65	71.1	41.7	4430.6	1.249	0.105833	0.894168
60	95.6	41.3	4218.4	0.961	0.168276	0.831724
55	58.9	40.8	4001.7	0.670	0.251429	0.748571
50	52.2	40.4	3781.0	0.374	0.354202	0.645798
45	45.5	40.1	3556.6	0.075	0.470107	0.529893

Table 5 Mean shear strength of material Vs Reliability-2

$\mu_p = 3500N, \sigma_p = 1000N, \sigma_{f_s} = 8\ N/mm^2,$
$\mu_d = 40\ mm,\ \sigma_d = 4\ mm,\ t_w = 1.25\ mm.$

μ_{f_s}	f_s	d	p	β	p_f	R
115	126.1	49.5	6345.3	3.958	0.000039	0.999961
110	120.9	48.6	6218.5	3.728	0.000097	0.999904
105	115.6	47.8	6079.3	3.494	0.000238	0.999762
100	110.3	47.0	5927.7	3.252	0.000573	0.999427
95	104.8	46.2	5764.0	3.001	0.001345	0.998655
90	99.3	45.4	5588.4	2.742	0.003053	0.996947
85	93.6	44.6	5401.4	2.474	0.006680	0.993320
80	87.9	43.9	5203.5	2.199	0.013939	0.986061
75	82.0	43.3	4999.3	1.916	0.027683	0.972318
70	76.1	42.6	4777.3	1.625	0.052081	0.947919
65	70.0	42.0	4550.3	1.328	0.092089	0.907911
60	60.0	41.5	4314.9	1.025	0.152682	0.847318
55	57.9	41.0	4071.9	0.715	0.237305	0.762696
50	51.6	40.5	3821.7	0.400	0.344578	0.655422

Table 6 Mean depth of the beam Vs Reliability-1

$\mu_p = 3500N, \sigma_p = 1000N, \sigma_{f_s} = 8\ N/mm^2,$
$\mu_{f_s} = 45\ N/mm^2, \sigma_d = 4\ mm, t_w = 1.25\ mm.$

μ_d	f_s	d	p	β	p_f	R
85	76.3	86.3	4874.6	4.159	0.000016	0.999984
80	74.2	81.5	4954.0	3.949	0.000039	0.999961
75	71.6	76.7	5019.8	3.696	0.000110	0.999891
70	68.8	71.9	5058.7	3.389	0.000351	0.999649
65	65.3	67.0	5051.5	3.089	0.001004	0.998996
60	61.4	62.0	4973.7	2.575	0.005012	0.994988
55	57.2	56.9	4799.3	2.053	0.020036	0.979964
50	52.8	51.5	4508.0	1.453	0.073112	0.926889
45	48.8	45.9	4093.1	0.789	0.215056	0.784944

4.2 Mean Depth of the Beam Vs Reliability

In the Table 6 reliability changes from 0.999984 to 0.784944 and reliability index from 4.159 to 0.789 when there is a change in mean depth of the beam from 85 mm to 45 mm at standard deviation 4 mm.

From the Table 7 it is clear that at standard deviation 2 mm of depth of the beam and mean depth from 90 mm to 40 mm reliability changes from 0.999993 to 0.533074 and reliability index changes from 4.34 to 0.083.

Table 7 Mean depth of the beam Vs Reliability-2

$\mu_p = 3500N, \sigma_p = 1000N, \sigma_{f_s} = 8\ N/mm^2,$
$\mu_{f_s} = 45\ N/mm^2, \sigma_d = 2\ mm, t_w = 1.25\ mm.$

μ_d	f_s	d	p	β	p_f	R
90	78.2	90.3	4783.0	4.340	0.000007	0.999993
85	76.5	85.3	4866.6	4.168	0.000015	0.999985
80	74.5	80.4	4945.7	3.962	0.000037	0.999963
75	72.1	75.4	5012.7	3.713	0.000102	0.999898
70	69.2	70.6	5055.4	3.412	0.000322	0.999678
65	65.9	65.5	5056.3	3.049	0.001148	0.998852
60	62.0	60.5	4991.4	2.612	0.004501	0.995499
55	57.8	55.5	4831.6	2.093	0.018175	0.981825
50	53.3	50.4	4548.9	1.490	0.068112	0.931888
45	49.0	45.2	4126.2	0.813	0.208109	0.791891
40	45.4	40.0	3569.4	0.083	0.466926	0.533074

5 Conclusion

Reliability analysis of simply supported I-beam under limit state shear and subjected to the point load at mid-point of span has been done by Hasofer and Lind method. In the analysis, strength of the material, depth of the section and load are assumed to follow normal distribution. Studied non-linear limit state function and normalized the basic variables and derived the iterative function to find reliability index. Used Matlab code for the design points at each level, calculated reliability and reliability index at each design point. From the calculations, the increment in load on the structural member from 2000N to 7000N at standard deviation 1000N effects the decrease of reliability index from 3.721 to 0.136 and reliability from 0.9999 to 0.554089. Increment in load from 2000N to 7000N at standard deviation 1000N effects the decrease of reliability index from 3.721 to 0.136 and reliability from 0.9999 to 0.554089. If the material strength changes from 115 N/mm^2 to 45 N/mm^2 reliability index decreases from 3.815 to 0.075 and reliability of the structural member decreases from 0.999932 to 0.529893. If the material strength changes from 115 N/mm^2 to 50 N/mm^2 causes decrease in the reliability from 0.999961 to 0.655422 and reliability index from 3.958 to 0.4. The reliability changes from 0.999984 to 0.784944 and reliability index from 4.159 to 0.789 when there is a change in mean depth of the beam from 85 mm to 45 mm at standard deviation 4 mm. At the standard deviation 2 mm of depth of the beam and mean depth from 90 mm to 40 mm reliability changes from 0.999993 to 0.533074 and reliability index changes from 4.34 to 0.083.

Future Scope of Work

One may study T-section, rectangular section of a beam for reliability and design point using Hasofer-Lind method. Linear and non–linear limit state functions may be taken for the analysis.

Ethics

The research work is not associated to safety, water and air pollution, the depletion of natural resources, loss of biodiversity, destruction of ecosystems, and global climate. The submitted work is original and not have been published elsewhere in any form or language.

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