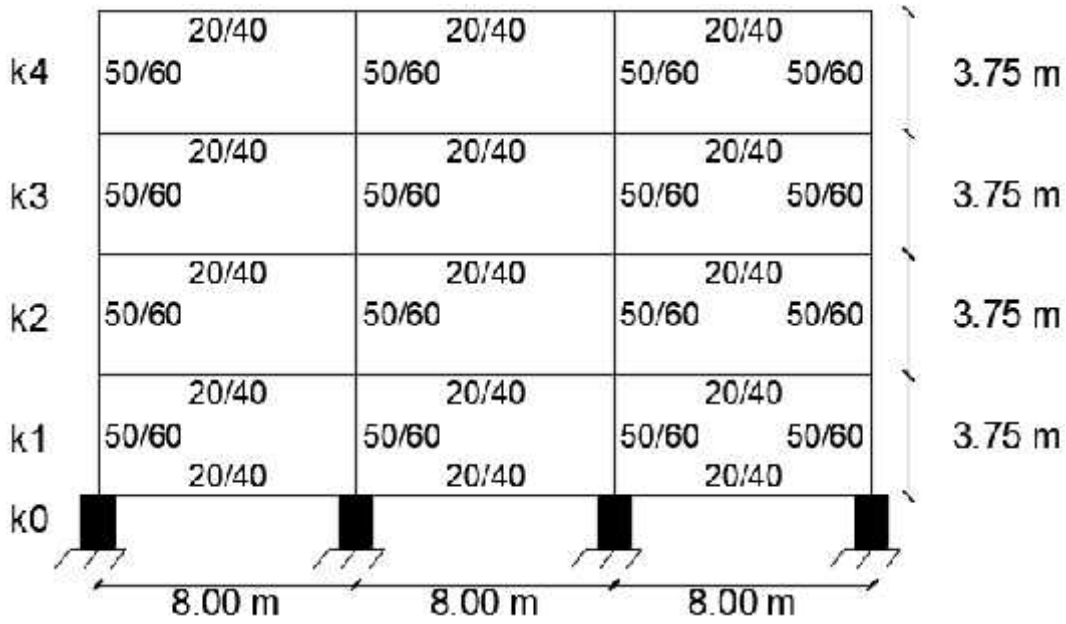
VERIFIKASI PERHITUNGAN

Verifikasi perhitungan yang digunakan adalah suatu model struktur beton 4 tingkat dengan beban data riwayat gempa El Centro 1940 yang dihitung dengan cara manual menggunakan Microsoft Excel 2003. Integrasi numerik yang digunakan adalah integrasi secara langsung persamaan differensial dependen (*Coupling*) dengan metode *β - Newmark*.

A. Perhitungan manual struktur 4 tingkat dengan isolasi dasar



Dimana diketahui data struktur dan data isolasi dasar:

- Data Struktur
  - q lantai = 2800 kg/m’
  - q atap = 2000 kg/m’
  - f’c = 25 Mpa
- Data Isolasi Dasar (IRHD-75)
  - Periode Target (T_D) = 2,5 detik
  - Regangan Geser (γ_{max}) = 50 %
  - Redaman Efektif (ξ_{eff}) = 10 % (IBC 2000, Tabel 1623.2.2.1)

Koefisien Redaman (B_D)= 1.2 (IBC 2000, Tabel 1623.2.2.1)

Koefisien Seismik (S_D) = 0.4 (IBC 2000, Tabel 1615.1.2(2))

Modulus elastisitas (E) = 940 N/cm²

Modulus Geser (G) = 222 N/cm²

Fator Modifikasi = 0.52

Baja A36: Fy = 274,4 MPa

Fs = 164,64 MPa

fpy = 8,82 MPa

1. Perhitungan Berat (W) Tiap – Tiap Tingkat

$$W_0 = panjang \times q$$
$$= (8\ m + 8\ m + 8\ m) \times 2800\ kg\ /\ m'$$
$$= 67200\ \ kg$$

$$W_1 = panjang \times q$$
$$= (8\ m + 8\ m + 8\ m) \times 2800\ kg\ /\ m'$$
$$= 67200\ \ kg$$

$$W_2 = panjang \times q$$
$$= (8\ m + 8\ m + 8\ m) \times 2800\ kg\ /\ m'$$
$$= 67200\ \ kg$$

$$W_3 = panjang \times q$$
$$= (8\ m + 8\ m + 8\ m) \times 2800\ kg\ /\ m'$$
$$= 67200\ \ kg$$

$$W_4 = panjang \times q$$
$$= (8\ m + 8\ m + 8\ m) \times 2000\ kg\ /\ m'$$
$$= 48000\ \ kg$$

Berat total struktur,

$$W = W_0 + W_1 + W_2 + W_3 + W_4$$
$$= 67200\ \ kg + 67200\ \ kg + 67200\ \ kg + 67200\ \ kg + 48000\ \ kg$$
$$= 316800\ \ kg$$

2. Perhitungan desain *Lead Rubber Bearing* (LRBs)

   a. Kekakuan efektif isolasi dasar

$$K_{eff} = \left(\frac{2®}{T}\right)^2 \frac{W}{g}$$

$$= \left(\frac{2®}{2{,}5\ dt}\right)^2 . \frac{316800\ kg}{980\ cm/dt^2} = 2041{,}9204\ kg/cm$$

   b. Simpangan maksimum isolasi dasar

$$D_D = \left(\frac{g}{4®^2}\right)\frac{S_D T_D}{B_D}$$

$$= \left(\frac{980}{4®^2}\right)^2 . \frac{0{,}4 \times 2{,}5}{1{,}2}' = 20{,}6864\ cm < 30\ cm \ \text{(oke)}$$

   c. Nilai leleh jangka pendek

$$Q_d = \frac{W_D}{4 D_D} = \frac{®}{2} K_{eff} ¶_{eff} D_D$$

$$= \frac{®}{2} \times 2041{,}9204 \times 10\% \times 20{,}6864 = 6635{,}0437\ kg$$

   d. Kekakuan setelah leleh

$$K_d = K_{eff} - \frac{Q_d}{D_D}$$

$$= 2041{,}9204 - \frac{6635{,}0437}{20{,}6864} = 1721{,}1763\ kg$$

   e. Luas penampang pada pusat inti

$$A_p = \frac{Q_d}{f_{py}}$$

$$= \frac{6635{,}0437}{8{,}84 \times 10{,}1972} = 73{,}7227\ cm^2$$

   f. Tinggi total karet

$$t_r = \frac{D_D}{¥_{max}}$$

$$= \frac{20{,}6864}{0{,}5} = 41{,}3728\,cm \rightarrow 42\,cm \text{ (pakai)}$$

g. Luas efektif dan ketebalan masing-masing lapisan karet

1) Faktor bentuk S

$$\frac{E \cdot (1 + 2kS^2)}{G} \geq 400 \rightarrow \frac{940 \cdot (1 + 2 \times 0{,}52S^2)}{222}$$

$$S > 9{,}4801 \rightarrow 20 \text{ (pakai)}$$

$$E_c = E \cdot (1 + 2kS^2) = 940 \cdot (1 + 2 \times 0{,}52 \times 20^2) = 391980\ N / cm^2$$

$$E_c = 39997{,}9592\ kg / cm^2$$

2) Luas penampang efaktif (A_0) pada bantalan berdasarkan tegangan geser izin untuk beban vertikal P_{DL+LL}

$$\pm_c = \frac{P_{DL+LL}}{A_0} \leq 80 kg / cm^2 \rightarrow \frac{316800}{A_0} \leq 80 kg / cm^2$$

$$A_0 > 3960\ cm^2$$

3) Luas penampang efaktif (A_1) pada bantalan dari regangan geser karena beban vertikal P_{DL+LL}

$$6S \frac{P_{DL+LL}}{E_c \cdot A_1} \leq \frac{£_b}{3} \rightarrow 6 \times 20 \times \frac{316800}{39997{,}9592 \cdot A_1} \leq \frac{500\%}{3}$$

$$A_1 > 570{,}2691\,cm^2$$

4) Kekakuan elastis (K_r) dari bantalan

$$K_d = K_r\left(1 + 12\frac{A_p}{A_0}\right) \rightarrow 1721{,}1763 = K_r\left(1 + 12\frac{73{,}7227}{3960}\right)$$

$$\rightarrow K_r = 1406{,}8770\ kg / cm$$

5) Luas penampang minimum (A_{sf}) untuk kegagalan geser bantalan

$$G = \frac{K_r \cdot t_r}{A_{sf}} \rightarrow A_{sf} = \frac{K_r \cdot t_r}{G} = \frac{1406{,}8770 \cdot 42}{(222/9{,}8)} = 2608{,}4260\,cm^2$$

Untuk bearing lingkaran dengan luas A_{sf} maka diamater d=57,6294 cm. Untuk menghitung luas penampang efektif A_2 dihitung mengunakan Persamaan 3.7 dan 3.8 maka A_2=976,7597 cm².

6) Menentukan luas penampang (A) yang diambil dari nilai maksimum A_0 , A_1 dan A_2

$$A = \max(A_0, A_1, A_2) = \max(3960;570,2691;976,7597) = 3960\ cm^2$$

Maka diameter dari luasasn A adalah d=71,0435 cm → d=75 cm (pakai)

7) Menentukan ukuran lapisan karet

$$= 2\cos^{-1}\left(\frac{D_D}{d}\right) = 2\cos^{-1}\left(\frac{16,5491}{75}\right) = 2,00001$$

$$A_{re} \le \frac{d^2}{4}(\quad -\sin\quad) \rightarrow \frac{75^2}{4}(2,00001 - \sin 2,00001) = 2763,4431\ cm^2$$

8) Menentukan tebal dan jumlah lapisan karet

$$S = \frac{d}{4t} \rightarrow 20 = \frac{75}{4t} \rightarrow t = 0,9375\ cm \rightarrow t = 1\ cm \text{ (pakai)}$$

h. Tebal pelat baja t_s

$$t_s \ge \frac{2(t_i + t_{s+1}) \cdot P_{DL+LL}}{A_{re} \cdot F_S} \ge 2\ mm$$

$$t_s \ge \frac{2(1+1) \cdot 316800}{2763,4431 \cdot (0,6 \times (222/9,8))} = 0,2732\ cm = 2,7323\ mm$$

$$t_s = 3\ mm \text{ (pakai)}$$

i. Tinggi total dari bearing dengan asumsi pelat penutup atas dan bawah tebal 2,5 cm

$$h = t_r + 41 \times t_s + 2 \times 2,5\ cm = 12\ cm + 41 \times 3\ mm + 5\ cm = 59,3\ cm$$

j. Cek regangan geser dan stabilitas LRBs

1) Persyaratan regangan geser akibat beban vertikal P_{DL+LL}

$$¥_{c,DL+LL} = 6S\frac{P_{DL+LL}}{E_c \cdot A} = 6 \times 20 \times \frac{316800}{39997,9592 \cdot 4417,8647} = 0,2154$$

$$\leq \frac{£_b}{3} = \frac{500\%}{3} = 1{,}6667 \rightarrow oke$$

2) Kondisi stabilitas

$$\pm_c = \frac{P}{A} = \frac{316800}{4417{,}8647} = 70{,}3464\ kg / cm^2$$

$$\leq \pm_c = \frac{G \cdot S \cdot L}{2{,}5 \cdot t_r} = \frac{(222 / 9{,}8) \times 20 \times 75}{2{,}5 \times 12} = 1132{,}6531 \rightarrow oke$$

3. Perhitungan Massa (m) Tiap – Tiap Tingkat

$$m_0 = \frac{W_0}{g} = \frac{67200\ kg}{980\ cm/dt^2} = 68{,}5714\ kg\ dt^2/cm$$

$$m_1 = \frac{W_1}{g} = \frac{67200\ kg}{980\ cm/dt^2} = 68{,}5714\ kg\ dt^2/cm$$

$$m_2 = \frac{W_2}{g} = \frac{67200\ kg}{980\ cm/dt^2} = 68{,}5714\ kg\ dt^2/cm$$

$$m_3 = \frac{W_3}{g} = \frac{67200\ kg}{980\ cm/dt^2} = 68{,}5714\ kg\ dt^2/cm$$

$$m_4 = \frac{W_4}{g} = \frac{48000\ kg}{980\ cm/dt^2} = 48{,}9796\ kg\ dt^2/cm$$

4. Menghitung Kekakuan Tingkat 1 / *Base Isolation*

$$K_0 = \frac{G \times A}{h}$$

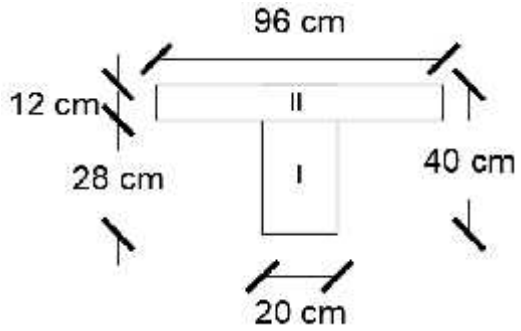
$$= \frac{(222 / 9.8)\ kg / cm^2 \times 0{,}25 \times ® \times (75\ cm)^2}{59{,}3\ cm} = 1687{,}6587\ kg / cm$$

5. Menghitung Momen Inersia Potongan

$$I_{c1} = \frac{1}{12} \times b \times h^3 = \frac{1}{12} \times 50cm \times 60^3 cm = 900000\ cm^4$$

$$I_{c1} = I_{c2} = I_{c3} = I_{c4}$$

Inertia balok T,



$$A_1 = b_1 \times h_1 = 20\ cm \times 28\ cm = 560\ cm^2$$

$$A_2 = b_2 \times h_2 = 96\ cm \times 12\ cm = 1152\ cm^2$$

$$y_1 = \frac{(ht - tp)}{2} = \frac{(40\ cm - 12\ cm)}{2} = 14\ cm$$

$$y_2 = ht - \frac{tp}{2} = 40\ cm - \frac{12\ cm}{2} = 34\ cm$$

$$y = \frac{A_1 \times y_1 + A_2 \times y_2}{A_1 + A_2} = \frac{(560\ cm^2 \times 14\ cm) + (1152\ cm^2 \times 34\ cm)}{560\ cm^2 + 1152\ cm^2}$$

$$= 27{,}4579\ cm$$

$$I_1 = \frac{1}{12} \times b_1 \times {h_1}^3 + A_1 \times (y - y_1)^2$$

$$= \frac{1}{12} \times 20\ cm \times 28^3\ cm + 560\ cm^2 \times (27{,}4579\ cm - 14\ cm)^2$$

$$= 138011{,}7694\ cm^4$$

$$I_2 = \frac{1}{12} \times b_2 \times {h_2}^3 + A_2 \times (y - y_2)^2$$

$$= \frac{1}{12} \times 96\ cm \times 12^3\ cm + 1152\ cm^2 \times (27{,}4579\ cm - 34\ cm)^2$$

$$= 63127{,}8693\ cm^4$$

$$I_b = I_1 + I_2 = 138011{,}7694\ cm^4 + 63127{,}8693\ cm^4 = 201139{,}6387\ cm^4$$

$$I_{b1} = I_{b2} = I_{b3}$$

6. Perhitungan Kekakuan Kolom Jepit-Jepit (Kj)

$$k_{c1} = \frac{12 \times E \times I}{L_1^{\,3}} = \frac{12 \times 4700\sqrt{25}\ MPa \times 10.2 \times 900000\ cm}{375^3\ cm} = 49090{,}56\ kg/cm$$

$$k_{c1} = k_{c2} = k_{c3} = k_{c4}$$

Kekakuan total,

$$K_j = k_{c1} + k_{c2} + k_{c3} + k_{c4}$$

$$= 49090{,}56 + 49090{,}56 + 49090{,}56 + 49090{,}56 = 196362{,}24\ kg/cm$$

7. Perhitungan Kekakuan dengan Cara Muto (Km)

a. Besaran EI/L

$$\frac{E \times I_{c1}}{L_{c1}} = \frac{4700\sqrt{25}\ MPa \times 10.2 \times 900000\ cm^4}{375\ cm} = 575280000\,cm^3$$

$$\frac{E \times I_{c1}}{L_{c1}} = \frac{E \times I_{c2}}{L_{c2}} = \frac{E \times I_{c3}}{L_{c3}} = \frac{E \times I_{c4}}{L_{c4}}$$

$$\frac{E \times I_{b1}}{L_{b1}} = \frac{4700\sqrt{25}\ MPa \times 10.2 \times 201139{,}6387\ cm^4}{800\ cm} = 60266464{,}2243 cm^3$$

$$\frac{E \times I_{b1}}{L_{b1}} = \frac{E \times I_{b2}}{L_{b2}} = \frac{E \times I_{b3}}{L_{b3}}$$

b. Nilai k

Diambil nilai konstanta K=575280000 cm³ maka,

$$k_{c1} = \frac{575280000 cm^3}{575280000 cm^3} = 1$$

$$k_{c1} = k_{c2} = k_{c3} = k_{c4}$$

$$k_{b1} = \frac{60266464{,}2243 cm^3}{575280000 cm^3} = 0{,}10476$$

$$k_{b1} = k_{b2} = k_{b3}$$

c. Nilai Cm

1) Koefisien kekakuan kolom tepi

$$C_{m1} = \frac{\sum k_{bi}}{\sum k_{bi} + 4k_c} = \frac{0{,}10476 + 0{,}10476}{(0{,}10476 + 0{,}10476) + 4 \times 1} = 0{,}04977$$

$$C_{m1} = C_{m2} = C_{m3} = C_{m4}$$

2) Koefisien kekakuan kolom tengah

$$C_{m1} = \frac{\sum k_{bi}}{\sum k_{bi} + 4k_c} = \frac{2 \times (0{,}10476 + 0{,}10476)}{2 \times (0{,}10476 + 0{,}10476) + 4 \times 1} = 0{,}09483$$

$$C_{m1} = C_{m2} = C_{m3} = C_{m4}$$

d. Kekakuan Kolom Total

$$K_m = C_m \times k_c$$

$$K_{m1} = 2 \times (0.04977 + 0{,}09482) \times 49090{,}56 = 14196{,}9126\ kg/cm$$

$$K_{m1} = K_{m2} = K_{m3} = K_{m4}$$

8. Rekapitulasi Massa (m) dan Kekakuan (k) Struktur

a. Massa

$$m_0 = 68{,}5714\ kg\ dt^2/cm$$

$$m_1 = 68{,}5714\ kg\ dt^2/cm$$

$$m_2 = 68{,}5714\ kg\ dt^2/cm$$

$$m_3 = 68{,}5714\ kg\ dt^2/cm$$

$$m_4 = 48{,}9796\ kg\ dt^2/cm$$

b. Kekakuan

$$k_0 = 1687{,}6587\ kg/cm$$

$$k_1 = 14196{,}9126\ kg/cm$$

$$k_2 = 14196{,}9126\ kg/cm$$

$$k_3 = 14196{,}9126\ kg/cm$$

$$k_4 = 14196{,}9126\ kg/cm$$

9. Perhitungan Mode Shapes

Matriks massa

$$[M]=\begin{bmatrix} m0 & 0 & 0 & 0 & 0 \\ 0 & m1 & 0 & 0 & 0 \\ 0 & 0 & m2 & 0 & 0 \\ 0 & 0 & 0 & m3 & 0 \\ 0 & 0 & 0 & 0 & m4 \end{bmatrix}$$

$$[M]=\begin{bmatrix} 68{,}5714 & 0 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 0 & 48{,}9796 \end{bmatrix}$$

Matriks kekakuan

$$[K]=\begin{bmatrix} k0+k1 & -k1 & 0 & 0 & 0 \\ -k1 & k1+k2 & -k2 & 0 & 0 \\ 0 & -k2 & k2+k3 & -k3 & 0 \\ 0 & 0 & -k3 & k3+k4 & -k4 \\ 0 & 0 & 0 & -k4 & k4 \end{bmatrix}$$

$$[K]=\begin{bmatrix} 15884{,}57 & -14196{,}91 & 0 & 0 & 0 \\ -14196{,}91 & 28393{,}83 & -14196{,}91 & 0 & 0 \\ 0 & -14196{,}91 & 28393{,}83 & -14196{,}91 & 0 \\ 0 & 0 & -14196{,}91 & 28393{,}83 & -14196{,}91 \\ 0 & 0 & 0 & -14196{,}91 & 14196{,}91 \end{bmatrix}$$

Apabila digunakan unit massa (m) = 68,5724 kg dt^2/cm dan unit kekakuan (k) = 14196,91 kg/cm, maka matriks massa tanah (m) dan matriks kekakuan tanah (k) diatas dapat ditulis kembali :

$$[M]=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0{,}7143 \end{bmatrix}$$

$$[K]=\begin{bmatrix} 1{,}1189 & -1 & 0 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 \\ 0 & -1 & 2 & -1 & 0 \\ 0 & 0 & -1 & 2 & -1 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix}$$

Dengan demikian dapat disusun persamaan *Eigen Problem* sebagai berikut

$$\begin{bmatrix} 1{,}1189-\alpha & -1 & 0 & 0 & 0 \\ -1 & 2-\alpha & -1 & 0 & 0 \\ 0 & -1 & 2-\alpha & -1 & 0 \\ 0 & 0 & -1 & 2-\alpha & -1 \\ 0 & 0 & 0 & -1 & 1-0{,}7143\alpha \end{bmatrix}.\begin{Bmatrix} \phi 0 \\ \phi 1 \\ \phi 2 \\ \phi 3 \\ \phi 4 \end{Bmatrix}=\begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

Kemudian persamaan – persamaan diatas dapat ditulis menjadi bentuk yang lebih sederhana seperti diberikan dibawah ini,

$$(1{,}1189-\alpha).\phi_0-\phi_1=0$$

$$-\phi_0+(2-\alpha).\phi_1-\phi_2=0$$

$$-\phi_1+(2-\alpha).\phi_2-\phi_3=0$$

$$-\phi_2+(2-\alpha).\phi_3-\phi_4=0$$

$$-\phi_3+(1-0{,}7143\alpha).\phi_4=0$$

Dengan mengambil nilai ϕ_0 = 1 yang selanjutnya nilai tersebut di distribusikan ke persamaan diatas, dengan metode distribusi aljabar biasa maka nilai mode yang lainnya dapat dicari. Hasilnya adalah sebagai berikut.

$$[\phi]=\begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1{,}0967 & 0{,}6465 & -0{,}4258 & -1{,}6688 & -2{,}5732 \\ 1{,}1691 & -0{,}0123 & -1{,}1939 & 0{,}3144 & 3{,}3540 \\ 1{,}2156 & -0{,}6653 & -0{,}1178 & 1{,}4211 & -3{,}1019 \\ 1{,}2352 & -1{,}0041 & 1{,}1402 & -1{,}4338 & 1{,}8947 \end{bmatrix}$$

Selanjutnya dapat dihitung nilai frekuensi sudut (ω) tiap Tingkat sebagai berikut ini,

$$\alpha_0=0{,}1332 \quad \rightarrow \quad \mu_0=\sqrt{\alpha_0.\frac{k}{m}}=\sqrt{0{,}1332.\frac{14196{,}91}{68{,}5714}}=2{,}1421\,\frac{rad}{dt}$$

$$\alpha_1=2{,}8381 \quad \rightarrow \quad \mu_1=\sqrt{\alpha_1.\frac{k}{m}}=\sqrt{2{,}8381.\frac{14196{,}91}{68{,}5714}}=9{,}8890\,\frac{rad}{dt}$$

$$a_2 = 9{,}2815 \quad \rightarrow \quad \mu_2 = \sqrt{a_2 . \frac{k}{m}} = \sqrt{9{,}2815 . \frac{14196{,}91}{68{,}5714}} = 17{,}8831 \frac{rad}{dt}$$

$$a_3 = 16{,}7502 \quad \rightarrow \quad \mu_3 = \sqrt{a_3 . \frac{k}{m}} = \sqrt{16{,}7502 . \frac{14196{,}91}{68{,}5714}} = 24{,}0240 \frac{rad}{dt}$$

$$a_4 = 22{,}1845 \quad \rightarrow \quad \mu_4 = \sqrt{a_4 . \frac{k}{m}} = \sqrt{22{,}1845 . \frac{14196{,}91}{68{,}5714}} = 27{,}6477 \frac{rad}{dt}$$

10. Kontrol Dengan Kondisi Partisipasi Mode :

a. Untuk mode ke – 0

$$P_0 = \{\phi\}_0^T . [M] \{I\}$$

$$P_0 = \begin{bmatrix} 1 & 1{,}0967 & 1{,}1691 & 1{,}2156 & 1{,}2325 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$

$$P_0 = 367{,}7969$$

$$M_0 = \{\phi\}_0^T . [M] \{\phi_0\}$$

$$M_0 = \begin{bmatrix} 1 & 1{,}0967 & 1{,}1691 & 1{,}2156 & 1{,}2325 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \begin{bmatrix} 1 \\ 1{,}0967 \\ 1{,}1691 \\ 1{,}2156 \\ 1{,}2352 \end{bmatrix}$$

$$M_0 = 420{,}8276$$

Partisipasi untuk mode ke – 0 : $\Gamma_0 = \frac{P_0}{M_0} = \frac{367{,}7969}{420{,}8276} = 0{,}8740$

b. Untuk mode ke – 1

$$P_1 = \{\phi\}_1^T . [M] \{I\}$$

$$P_1 = \begin{bmatrix} 1 & 0{,}6465 & -0{,}0123 & -0{,}6653 & -1{,}0041 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$

$$P_1 = 17{,}2577$$

$$M_1 = \{\phi\}_1^T . [M] \{\phi_1\}$$

$$M_1 = \begin{bmatrix} 1 & 0{,}6465 & -0{,}0123 & -0{,}6653 & -1{,}0041 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \begin{bmatrix} 1 \\ 0{,}6465 \\ -0{,}0123 \\ -0{,}6653 \\ -1{,}0041 \end{bmatrix}$$

$$M_1 = 176{,}9832$$

Partisipasi untuk mode ke – 1 : $\Gamma_1 = \dfrac{P_1}{M_1} = \dfrac{17{,}2577}{176{,}9832} = 0{,}0975$

c. Untuk mode ke – 2

$$P_2 = \{¤\}_2^T . [M] \{I\}$$

$$P_2 = \begin{bmatrix} 1 & -0{,}4258 & -1{,}1939 & -0{,}1178 & 1{,}1402 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$

$$P_2 = 5{,}2771$$

$$M_2 = \{¤\}_2^T . [M] . \{¤_2\}$$

$$M_2 = \begin{bmatrix} 1 & -0{,}4258 & -1{,}1939 & -0{,}1178 & 1{,}1402 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \begin{bmatrix} 1 \\ -0{,}4258 \\ -1{,}1939 \\ -0{,}1178 \\ 1{,}1402 \end{bmatrix}$$

$$M_2 = 243{,}3723$$

Partisipasi untuk mode ke – 2 : $\Gamma_2 = \dfrac{P_2}{M_2} = \dfrac{5{,}2771}{243{,}3723} = 0{,}0217$

d. Untuk mode ke – 3

$$P_3 = \{¤\}_3^T . [M] \{I\}$$

$$P_3 = \begin{bmatrix} 1 & -1{,}6688 & 0{,}3144 & 1{,}4211 & -1{,}4338 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$

$$P_3 = 2{,}9241$$

$$M_3 = \{¤\}_3^T . [M] \{¤_3\}$$

$$M_3 = \begin{bmatrix} 1 & -1{,}6688 & 0{,}3144 & 1{,}4211 & -1{,}4338 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \begin{bmatrix} 1 \\ -1{,}6688 \\ 0{,}3144 \\ 1{,}4211 \\ -1{,}4338 \end{bmatrix}$$

$$M_3 = 505{,}4834$$

Partisipasi untuk mode ke – 3 : $\Gamma_3 = \dfrac{P_3}{M_3} = \dfrac{2{,}9241}{505{,}4834} = 0{,}0058$

e. Untuk mode ke – 4

$$P_4 = \{\text{¤}\}_4^T . [M] \{I\}$$

$$P_4 = \begin{bmatrix} 1 & -2{,}5732 & 3{,}3540 & -3{,}1019 & 1{,}8947 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$

$$P_4 = 2{,}2078$$

$$M_4 = \{\text{¤}\}_4^T . [M] \{\text{¤}_4\}$$

$$M_4 = \begin{bmatrix} 1 & -2{,}5732 & 3{,}3540 & -3{,}1019 & 1{,}8947 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \begin{bmatrix} 1 \\ -2{,}5732 \\ 3{,}3540 \\ -3{,}1019 \\ 1{,}8947 \end{bmatrix}$$

$$M_4 = 2129{,}5905$$

Partisipasi untuk mode ke – 4 : $\Gamma_4 = \dfrac{P_4}{M_4} = \dfrac{2{,}2078}{2129{,}5905} = 0{,}0010$

Sebagai kontrol bahwa jumlah partisipasi mode harus sama dengan satu, maka

$$\sum \Gamma = \Gamma_0 + \Gamma_1 + \Gamma_2 + \Gamma_3 + \Gamma_4$$

$$= 0{,}8740 + 0{,}0975 + 0{,}0217 + 0{,}0058 + 0{,}0010$$

$$= 1 \quad \text{(memenuhi syarat)}$$

11. Perhitungan Matriks Redaman (C)

Dalam analisis digunakan matriks redaman dengan metode *Mass and Stiffness Proportional Damping* dengan nilai redaman (ξ) = 0,05

Frekuensi sudut yang akan dijadikan referensi (ω_i) diambil pada mode ke – 3 yaitu 18,0611 rad/dt dan (ω_j) pada mode ke -1 yaitu 2,7886 rad/dt.

$$= \frac{2(\P_j.\mu_j - \P_i.\mu_i)}{\mu_j^{\ 2} - \mu_i^{\ 2}} = \frac{2(0,05.17,8831 - 0,05.2,1421)}{17,8831^2 - 2,1421^2} = 0,0049$$

$$\sim = 2.\P_j.\mu_j - \quad .\mu_j^{\ 2} = 2.0,05.17,8831 - 0,0049.17,8831^2 = 0,1913$$

Matriks redaman :

$$[C] = \sim.[M] + \quad .[K]$$

$$\sim.[M] = 0,1913.\begin{bmatrix} 68,5714 & 0 & 0 & 0 & 0 \\ 0 & 68,5714 & 0 & 0 & 0 \\ 0 & 0 & 68,5714 & 0 & 0 \\ 0 & 0 & 0 & 68,5714 & 0 \\ 0 & 0 & 0 & 0 & 48,9796 \end{bmatrix} +$$

$$.[K] = 0,0049\begin{bmatrix} 1588,57 & -1419,91 & 0 & 0 & 0 \\ -1419,91 & 2839,83 & -1419,91 & 0 & 0 \\ 0 & -1419,91 & 2839,83 & -1419,91 & 0 \\ 0 & 0 & -1419,91 & 2839,83 & -1419,91 \\ 0 & 0 & 0 & -1419,91 & 1419,91 \end{bmatrix}$$

Maka nilai matrik redaman [C] adalah :

$$[C] = \begin{bmatrix} 92,4404 & -70,8953 & 0 & 0 & 0 \\ -70,8953 & 154,9080 & -70,8953 & 0 & 0 \\ 0 & -70,8953 & 154,9080 & -70,8953 & 0 \\ 0 & 0 & -70,8953 & 154,9080 & -70,8953 \\ 0 & 0 & 0 & -70,8953 & 80,2649 \end{bmatrix}$$

12. Integrasi Langsung *β-Newmark*

a. Mencari kekakuan efektif ($\hat{K}$)

Dalam mencari kekakuan efektif ditentukan terlebih dahulu nilai γ = 0,50 dan nilai β = 0,25. Kemudian nilai kekakuan efektif dihitung dengan rumus sebagai berikut :

$$\hat{K} = [K] + \left\{ \frac{¥}{\times \Delta t} \times [C] \right\} + \left\{ \frac{1}{\times \Delta t^2} \times [M] \right\}$$

$$\hat{K} = \left[\begin{bmatrix} 15884,57 & -14196,91 & 0 & 0 & 0 \\ -14196,91 & 28393,83 & -14196,91 & 0 & 0 \\ 0 & -14196,91 & 28393,83 & -14196,91 & 0 \\ 0 & 0 & -14196,91 & 28393,83 & -14196,91 \\ 0 & 0 & 0 & -14196,91 & 14196,91 \end{bmatrix} \right] +$$

$$\left\{ \frac{0,50}{0,25 \times 0,01} \times \begin{bmatrix} 92,4404 & -70,8953 & 0 & 0 & 0 \\ -70,8953 & 154,9080 & -70,8953 & 0 & 0 \\ 0 & -70,8953 & 154,9080 & -70,8953 & 0 \\ 0 & 0 & -70,8953 & 154,9080 & -70,8953 \\ 0 & 0 & 0 & -70,8953 & 80,2649 \end{bmatrix} \right\} +$$

$$\left\{ \frac{1}{0,25 \times \left(0,01^2\right)} \times \begin{bmatrix} 68,5714 & 0 & 0 & 0 & 0 \\ 0 & 68,5714 & 0 & 0 & 0 \\ 0 & 0 & 68,5714 & 0 & 0 \\ 0 & 0 & 0 & 68,5714 & 0 \\ 0 & 0 & 0 & 0 & 48,9796 \end{bmatrix} \right\}$$

$$\hat{K} = \begin{bmatrix} 2777229,787 & -28375,971 & 0 & 0 & 0 \\ -28375,971 & 2802232,563 & -28375,971 & 0 & 0 \\ 0 & -28375,971 & 2802232,563 & -28375,971 & 0 \\ 0 & 0 & -28375,971 & 2802232,563 & -28375,971 \\ 0 & 0 & 0 & -28375,971 & 1989433,558 \end{bmatrix}$$

b. Mencari konstanta a

$$a = \left\{ \frac{1}{\times \Delta t} \times [M] \right\} + \left\{ \frac{¥}{} \times [C] \right\}$$

$$a = \left\{ \frac{1}{0,25 \times 0,01} \times \begin{bmatrix} 68,5714 & 0 & 0 & 0 & 0 \\ 0 & 68,5714 & 0 & 0 & 0 \\ 0 & 0 & 68,5714 & 0 & 0 \\ 0 & 0 & 0 & 68,5714 & 0 \\ 0 & 0 & 0 & 0 & 48,9796 \end{bmatrix} \right\} +$$

$$\left\{ \frac{0,50}{0,25} \times \begin{bmatrix} 92,4404 & -70,8953 & 0 & 0 & 0 \\ -70,8953 & 154,9080 & -70,8953 & 0 & 0 \\ 0 & -70,8953 & 154,9080 & -70,8953 & 0 \\ 0 & 0 & -70,8953 & 154,9080 & -70,8953 \\ 0 & 0 & 0 & -70,8953 & 80,2649 \end{bmatrix} \right\}$$

$$a = \begin{bmatrix} 27613,452 & -141,791 & 0 & 0 & 0 \\ -141,791 & 27738,387 & -141,791 & 0 & 0 \\ 0 & -141,791 & 27738,387 & -141,791 & 0 \\ 0 & 0 & -141,791 & 27738,387 & -141,791 \\ 0 & 0 & 0 & -141,791 & 19752,367 \end{bmatrix}$$

c. Mencari konstanta b

$$b = \left\{ \frac{1}{2\times} \times [M] \right\} + \left\{ \left(\frac{¥}{2\times} - 1 \right) \times \Delta t \times [C] \right\}$$

$$b = \left\{ \frac{1}{2 \times 0,25} \times \left[\begin{bmatrix} 68,5714 & 0 & 0 & 0 & 0 \\ 0 & 68,5714 & 0 & 0 & 0 \\ 0 & 0 & 68,5714 & 0 & 0 \\ 0 & 0 & 0 & 68,5714 & 0 \\ 0 & 0 & 0 & 0 & 48,9796 \end{bmatrix} \right] \right\} +$$

$$\left\{ \left(\frac{0,50}{2 \times 0,25} - 1 \right) \times 0,01 \times \begin{bmatrix} 92,4404 & -70,8953 & 0 & 0 & 0 \\ -70,8953 & 154,9080 & -70,8953 & 0 & 0 \\ 0 & -70,8953 & 154,9080 & -70,8953 & 0 \\ 0 & 0 & -70,8953 & 154,9080 & -70,8953 \\ 0 & 0 & 0 & -70,8953 & 80,2649 \end{bmatrix} \right\}$$

$$b = \begin{bmatrix} 137,1429 & 0 & 0 & 0 & 0 \\ 0 & 137,1429 & 0 & 0 & 0 \\ 0 & 0 & 137,1429 & 0 & 0 \\ 0 & 0 & 0 & 137,1429 & 0 \\ 0 & 0 & 0 & 0 & 97,9592 \end{bmatrix}$$

d. Perhitungan Pembebanan Siklus Ke – 1 dimana i = 0

Perhitungan pembebanan menggunakan beban riwayat gempa El Centro 1940 dimana data riwayat percepatan gempanya disajikan dalam dibawah ini.

Waktu (detik)	Percepatan Gempa (cm/dt^2)
0,00	0
0,01	0
0,02	1,6954
0,03	3,3810
0.04	5,0764
0.05	6,7620
dst	dst

Dimana diketahui pada kondisi awal bahwa nilai :

Simpangan → $y_0 = 0$

Kecepatan → $\dot{y}_0 = 0$

Percepatan → $\ddot{y}_0 = 0$

1) Mencari nilai pertambahan pembebanan ($\Delta\hat{P}_i$)

$$\Delta\hat{P}_i = \left\{ \left(\ddot{y}_{b,i+1} - \ddot{y}_{b,i} \right) \times [M] \right\} + \left(a \times [\dot{y}_i] \right) + \left(b \times [\ddot{y}_i] \right)$$

$$\Delta\hat{P}_0 = \left\{ \left(\ddot{y}_{b,0+1} - \ddot{y}_{b,0} \right) \times [M] \right\} + \left([a] \times [\dot{y}_0] \right) + \left([b] \times [\ddot{y}_0] \right)$$

$$\Delta\hat{P}_0 = \left\{ \left(\ddot{y}_{b,1} - \ddot{y}_{b,0} \right) \times [M] \right\} + \left([a] \times [\dot{y}_0] \right) + \left([b] \times [\ddot{y}_0] \right)$$

$$= \left\{ (1{,}6954 - 0{,}0000) \times \begin{bmatrix} 68{,}5714 \\ 68{,}5714 \\ 68{,}5714 \\ 68{,}5714 \\ 48{,}9796 \end{bmatrix} \right\}$$

$$+\left(\begin{bmatrix} 27613{,}452 & -141{,}791 & 0 & 0 & 0 \\ -141{,}791 & 27738{,}387 & -141{,}791 & 0 & 0 \\ 0 & -141{,}791 & 27738{,}387 & -141{,}791 & 0 \\ 0 & 0 & -141{,}791 & 27738{,}387 & -141{,}791 \\ 0 & 0 & 0 & -141{,}791 & 19752{,}367 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}\right)$$

$$+\left(\begin{bmatrix} 137{,}1429 & 0 & 0 & 0 & 0 \\ 0 & 137{,}1429 & 0 & 0 & 0 \\ 0 & 0 & 137{,}1429 & 0 & 0 \\ 0 & 0 & 0 & 137{,}1429 & 0 \\ 0 & 0 & 0 & 0 & 97{,}9592 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}\right)$$

$$\Delta\hat{P}_0 = \begin{bmatrix} 116{,}256 \\ 116{,}256 \\ 116{,}256 \\ 116{,}256 \\ 83{,}040 \end{bmatrix}$$

2) Mencari nilai pertambahan simpangan (Δy_i)

$$\hat{K}.\Delta y_i = \Delta\hat{P}_i$$

$$\hat{K}.\Delta y_0 = \Delta\hat{P}_0$$

$$\begin{bmatrix} 2777229{,}787 & -28375{,}971 & 0 & 0 & 0 \\ -28375{,}971 & 2802232{,}563 & -28375{,}971 & 0 & 0 \\ 0 & -28375{,}971 & 2802232{,}563 & -28375{,}971 & 0 \\ 0 & 0 & -28375{,}971 & 2802232{,}563 & -28375{,}971 \\ 0 & 0 & 0 & -28375{,}971 & 1989433{,}558 \end{bmatrix} \Delta y_0 = \begin{bmatrix} 116{,}256 \\ 116{,}256 \\ 116{,}256 \\ 116{,}256 \\ 83{,}040 \end{bmatrix}$$

$$\Delta y_o = \begin{bmatrix} 4{,}22931 \times 10^{-5} \\ 4{,}23440 \times 10^{-5} \\ 4{,}23445 \times 10^{-5} \\ 4{,}23445 \times 10^{-5} \\ 4{,}23445 \times 10^{-5} \end{bmatrix}$$

3) Mencari nilai pertambahan kecepatan (Δy_i)

$$\Delta\dot{y}_i = \left(\frac{¥}{\times \Delta t} \times [\Delta y_i] \right) - \left(\frac{¥}{—} \times [\dot{y}_i] \right) + \left(1 - \frac{¥}{2} \right) . \Delta t . [\ddot{y}_i]$$

$$\Delta\dot{y}_0 = \left(\frac{¥}{\times \Delta t} \times [\Delta y_0] \right) - \left(\frac{¥}{—} \times [\dot{y}_0] \right) + \left(1 - \frac{¥}{2} \right) . \Delta t . [\ddot{y}_0]$$

$$\Delta\dot{y}_0 = \left(\frac{0{,}50}{0{,}25 \times 0{,}01} \times \begin{bmatrix} 4{,}22931 \times 10^{-5} \\ 4{,}23440 \times 10^{-5} \\ 4{,}23445 \times 10^{-5} \\ 4{,}23445 \times 10^{-5} \\ 4{,}23445 \times 10^{-5} \end{bmatrix} \right) - \left(\frac{0{,}50}{0{,}25} \times \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \right)$$

$$+ \left(1 - \frac{0{,}50}{2.0{,}25} \right) . 0{,}01 . \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\Delta\dot{y}_0 = \begin{bmatrix} 0{,}0084586 \\ 0.0084688 \\ 0.0084689 \\ 0.0084689 \\ 0.0084689 \end{bmatrix}$$

4) Mencari nilai pertambahan percepatan ($\Delta\ddot{y}_i$)

$$\Delta\ddot{y}_i = \left(\frac{1}{\times \Delta t^2} \times [\Delta y_i] \right) - \left(\frac{1}{\times \Delta t} \times [\dot{y}_i] \right) - \left(\frac{1}{2} \times [\ddot{y}_i] \right)$$

$$\Delta\ddot{y}_0 = \left(\frac{1}{\times \Delta t^2} \times [\Delta y_0] \right) - \left(\frac{1}{\times \Delta t} \times [\dot{y}_0] \right) - \left(\frac{1}{2} \times [\ddot{y}_0] \right)$$

$$= \left(\frac{1}{0{,}25 \times 0{,}01^2} \times \begin{bmatrix} 4{,}22931 \times 10^{-5} \\ 4{,}23440 \times 10^{-5} \\ 4{,}23445 \times 10^{-5} \\ 4{,}23445 \times 10^{-5} \\ 4{,}23445 \times 10^{-5} \end{bmatrix} \right) - \left(\frac{1}{0{,}25 \times 0{,}01} \times \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \right)$$

$$-\left(\frac{1}{2\times 0{,}25}\times\begin{bmatrix}0\\0\\0\\0\\0\end{bmatrix}\right)$$

$$\Delta\ddot{y}_0=\begin{bmatrix}1{,}6917224\\1{,}6937591\\1{,}6937797\\1{,}6937799\\1{,}6937799\end{bmatrix}$$

5) Maka besarnya simpangan akhir interval (y_{i+1}) adalah :

$$y_{i+1}=y_i+\Delta y_i$$

$$y_{0+1}=y_0+\Delta y_0$$

$$y_1=y_0+\Delta y_0$$

$$\begin{bmatrix}y_0\\y_1\\y_2\\y_3\\y_4\end{bmatrix}_{siklus\ ke-1}=\begin{bmatrix}0\\0\\0\\0\\0\end{bmatrix}+\begin{bmatrix}4{,}22931\times10^{-5}\\4{,}23440\times10^{-5}\\4{,}23445\times10^{-5}\\4{,}23445\times10^{-5}\\4{,}23445\times10^{-5}\end{bmatrix}=\begin{bmatrix}4{,}22931\times10^{-5}\\4{,}23440\times10^{-5}\\4{,}23445\times10^{-5}\\4{,}23445\times10^{-5}\\4{,}23445\times10^{-5}\end{bmatrix}$$

6) Menghitung simpangan netto (y_n)

$$y_n=y_i-y_{base}$$

a) Tingkat 0 / *Base Isolation*

$$y_{00}=4{,}22931\times10^{-5}-4{,}22931\times10^{-5}=0$$

b) Tingkat 1

$$y_{01}=4{,}23440\times10^{-5}-4{,}22931\times10^{-5}=5{,}09156\times10^{-8}$$

c) Tingkat 2

$$y_{02}=4{,}23445\times10^{-5}-4{,}22931\times10^{-5}=5{,}14312\times10^{-8}$$

d) Tingkat 3

$$y_{03} = 4{,}23445 \times 10^{-5} - 4{,}22931 \times 10^{-5} = 5{,}14365 \times 10^{-8}$$

e) Tingkat 4

$$y_{04} = 4{,}23445 \times 10^{-5} - 4{,}22931 \times 10^{-5} = 5{,}14365 \times 10^{-8}$$

jika disusun dalam bentuk matrik maka,

$$y_n = \begin{bmatrix} 0 \\ 5{,}09156 \times 10^{-8} \\ 5{,}14312 \times 10^{-8} \\ 5{,}14365 \times 10^{-8} \\ 5{,}14365 \times 10^{-8} \end{bmatrix}$$

7) Menghitung simpangan antar tingkat / *interstorey drift* (yy)

$$yy = y_n - y_{n-1}$$

a) Tingkat 0 / *Base Isolation*

$$yy_{00} = 0 - 0 = 0$$

b) Tingkat 1

$$yy_{01} = 5{,}09156 \times 10^{-8} - 0 = 5{,}09156 \times 10^{-8}$$

c) Tingkat 2

$$yy_{12} = 5{,}14312 \times 10^{-8} - 5{,}09156 \times 10^{-8} = 5{,}15635 \times 10^{-10}$$

d) Tingkat 3

$$yy_{23} = 5{,}14365 \times 10^{-8} - 5{,}14312 \times 10^{-8} = 5{,}22195 \times 10^{-12}$$

e) Tingkat 4

$$yy_{14} = 5{,}14365 \times 10^{-8} - 5{,}14365 \times 10^{-8} = 5{,}26652 \times 10^{-14}$$

jika disusun dalam bentuk matrik maka,

$$yy = \begin{bmatrix} 0 \\ 5{,}09156 \times 10^{-8} \\ 5{,}15635 \times 10^{-10} \\ 5{,}22195 \times 10^{-12} \\ 5{,}26652 \times 10^{-14} \end{bmatrix}$$

8) Maka besarnya kecepatan akhir interval ($\dot{y}_{i+1}$) adalah :

$$\dot{y}_{i+1} = \dot{y}_i + \Delta\dot{y}_i$$

$$\dot{y}_{0+1} = \dot{y}_0 + \Delta\dot{y}_0$$

$$\dot{y}_1 = \dot{y}_0 + \Delta\dot{y}_0$$

$$\begin{bmatrix} \dot{y}_0 \\ \dot{y}_1 \\ \dot{y}_2 \\ \dot{y}_3 \\ \dot{y}_4 \end{bmatrix}_{siklus\ ke-1} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0{,}0084586 \\ 0.0084688 \\ 0.0084689 \\ 0.0084689 \\ 0.0084689 \end{bmatrix} = \begin{bmatrix} 0{,}0084586 \\ 0.0084688 \\ 0.0084689 \\ 0.0084689 \\ 0.0084689 \end{bmatrix}$$

9) Maka besarnya percepatan akhir interval ($\ddot{y}_{i+1}$) adalah :

$$\ddot{y}_{i+1} = \ddot{y}_i + \Delta\ddot{y}_i$$

$$\ddot{y}_{0+1} = \ddot{y}_0 + \Delta\ddot{y}_0$$

$$\ddot{y}_1 = \ddot{y}_0 + \Delta\ddot{y}_0$$

$$\begin{bmatrix} \ddot{y}_0 \\ \ddot{y}_1 \\ \ddot{y}_2 \\ \ddot{y}_3 \\ \ddot{y}_4 \end{bmatrix}_{siklus\ ke-1} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 1{,}6917224 \\ 1{,}6937591 \\ 1{,}6937797 \\ 1{,}6937799 \\ 1{,}6937799 \end{bmatrix} = \begin{bmatrix} 1{,}6917224 \\ 1{,}6937591 \\ 1{,}6937797 \\ 1{,}6937799 \\ 1{,}6937799 \end{bmatrix}$$

10) Menghitung rasio simpangan antar tingkat / *interstorey drift ratio* (yr)

$$yr = \frac{yy_i}{h} \times 100$$

a) Tingkat 0 / *Base Isolation*

$$y_{r0} = \frac{0}{59.3} \times 100 = 0\%$$

b) Tingkat 1

$$y_{r1} = \frac{5{,}09156 \times 10^{-8}}{375} \times 100 = 1{,}35775 \times 10^{-8}\%$$

c) Tingkat 2

$$y_{r2} = \frac{5{,}15635 \times 10^{-10}}{375} \times 100 = 1{,}37503 \times 10^{-10}\%$$

d) Tingkat 3

$$y_{r3} = \frac{5{,}22195 \times 10^{-12}}{375} \times 100 = 1{,}39252 \times 10^{-12}\%$$

e) Tingkat 4

$$y_{r4} = \frac{5{,}26652 \times 10^{-14}}{375} \times 100 = 1{,}40441 \times 10^{-14}\%$$

11) Menghitung gaya horizontal tingkat (F)

$$F = y_n \times [K]$$

$$F = \begin{bmatrix} 0 \\ 5{,}092 \times 10^{-8} \\ 5{,}143 \times 10^{-8} \\ 5{,}144 \times 10^{-8} \\ 5{,}144 \times 10^{-8} \end{bmatrix} \times \begin{bmatrix} 15884{,}57 & -14196{,}91 & 0 & 0 & 0 \\ -14196{,}91 & 28393{,}83 & -14196{,}91 & 0 & 0 \\ 0 & -14196{,}91 & 28393{,}83 & -14196{,}91 & 0 \\ 0 & 0 & -14196{,}91 & 28393{,}83 & -14196{,}91 \\ 0 & 0 & 0 & -14196{,}91 & 14196{,}91 \end{bmatrix}$$

$$= \begin{bmatrix} -0{,}00072 \\ 0{,}000716 \\ 7{,}24628 \times 10^{-6} \\ 7{,}33879 \times 10^{-8} \\ 7{,}47684 \times 10^{-10} \end{bmatrix} \text{kg}$$

12) Menghitung gaya geser tingkat (V)

$$V = \sum_{j=i}^{n} F_j$$

a) Tingkat 0 / *Base Isolation*

$$V_1 = F_0 + F_1 + F_2 + F_3 + F_4$$

$$= -0.00072 + 0{,}000716 + 7{,}24628 \times 10^{-6} + 7{,}33879 \times 10^{-8} + 7{,}47684 \times 10^{-10}$$

$$= 0 \text{ kg}$$

b) Tingkat 1

$$V_1 = F_1 + F_2 + F_3 + F_4$$

$$= 0{,}000716 + 7{,}24628 \times 10^{-6} + 7{,}33879 \times 10^{-8} + 7{,}47684 \times 10^{-10}$$

$$= 0{,}000723 \text{ kg}$$

c) Tingkat 2

$$V_2 = F_2 + F_3 + F_4$$

$$= 7{,}24628\times10^{-6} + 7{,}33879\times10^{-8} + 7{,}47684\times10^{-10}$$

$$= 7{,}32042\times10^{-6}\,\text{kg}$$

d) Tingkat 3

$$V_3 = F_3 + F_4$$

$$= 7{,}33879\times10^{-8} + 7{,}47684\times10^{-10}$$

$$= 7{,}41356\times10^{-8}\,\text{kg}$$

e) Tingkat 4

$$V_4 = F_4$$

$$= 7{,}47684\times10^{-10}\,\text{kg}$$

13) Menghitung momen guling (Mg)

$$M_g = \sum_{j=i}^{n} F_j \times H_j$$

a) Dasar

$$M_{gdasar} = (F_0 \times H_0) + (F_1 \times H_1) + (F_2 \times H_2) + (F_3 \times H_3) + (F_4 \times H_4)$$

$$= -0{,}000723\times59{,}3 + 0{,}000716\times375 + 7{,}24628\times10^{-6}\times375 +$$

$$7{,}33879\times10^{-8}\times375 + 7{,}47684\times10^{-10}\times375$$

$$= 0{,}228202\ \text{kg.cm}$$

b) Tingkat 0 / *Base Isolation*

$$M_{g0} = (F_1 \times H_1) + (F_2 \times H_2) + (F_3 \times H_3) + (F_4 \times H_4)$$

$$= 0{,}000716\times375 + 7{,}24628\times10^{-6}\times375 + 7{,}33879\times10^{-8}\times375$$

$$7{,}47684\times10^{-10}\times375$$

$$= 0{,}271067\ \text{kg.cm}$$

c) Tingkat 1

$$M_{g1} = (F_2 \times H_2) + (F_3 \times H_3) + (F_4 \times H_4)$$

$$= 7{,}24628\times10^{-6}\times375 + 7{,}33879\times10^{-8}\times375$$

$$7{,}47684\times10^{-10}\times375$$

$$= 0.002745 \text{ kg.cm}$$

d) Tingkat 2

$$M_{g2} = (F_3 \times H_3) + (F_4 \times H_4)$$

$$= 7{,}33879\times10^{-8}\times375 + 7{,}47684\times10^{-10}\times375$$

$$= 2{,}78009\times10^{-5} \text{ kg.cm}$$

e) Tingkat 3

$$M_{g3} = (F_4 \times H_4)$$

$$= 7{,}47684\times10^{-10}\times375$$

$$= 2{,}80381\times10^{-7} \text{ kg.cm}$$

f) Tingkat 4

$$M_{g4} = 0 \text{ kg.cm}$$

14) Perhitungan Regangan Geser Untuk Tiap Tingkat (γ_i)

a) Tingkat 0 / *Base Isolation*

$$¥_0 = \left(\frac{y_0 - 0}{h_0}\right) = \left(\frac{4{,}22931\times10^{-5}\ cm - 0\ cm}{59{,}3\ cm}\right) = 7{,}13205\times10^{-7}$$

15) Perhitungan Modulus Geser (G_i)

a) Tingkat 1 / *Base Isolation*

$$G_i = \frac{1}{1 + \sim\left(\frac{¥^{\sim}}{¥_h}\right)} \times G_0$$

$$G_0 = \frac{1}{1 + 0.97\left(\frac{\left(7{,}13205\times10^{-7}\right)^{0{,}97}}{1{,}1}\right)} \times 22{,}6531\ kg/cm^2 = 22{,}65304\ kg/cm^2$$

16) Perhitungan Kekakuan Struktur Tiap Step (K_i)

a) Tingkat 0 / *Base Isolation*

$$K_1 = \frac{G_1 \times A}{h}$$

$$K_i = \frac{22{,}65304\ kg/cm^2 \times 0{,}25 \times ® \times (75\ cm)^2}{59{,}3} = 1687{,}6570\ kg/cm$$

b) Tingkat 1

$K_1 = 14196{,}9126\ kg/cm$

c) Tingkat 2

$K_2 = 14196{,}9126\ kg/cm$

d) Tingkat 3

$K_3 = 14196{,}9126\ kg/cm$

e) Tingkat 4

$K_4 = 14196{,}9126\ kg/cm$

17) Perhitungan Tegangan Leleh (τ_y)

a) Tingkat 0 / *Base Isolation*

$$²_y = \frac{0{,}1 \times W}{A}$$

$$= \frac{0{,}1 \times 316800\ kg}{0{,}25 \times ® \times 75^2} = 7{,}1709\ kg/cm^2$$

18) Perhitungan Regangan Leleh (γ_y)

a) Tingkat 0 / *Base Isolation*

$$¥_y = \frac{²_y}{G} = \frac{7{,}1709\ kg/cm^2}{22{,}6530\ kg/cm^2} = 0{,}3166$$

19) Perhitungan c pemisalan

a) Tingkat 0 / *Base Isolation*

$$c = \frac{¥_0}{¥_y} = \frac{7{,}13205 \times 10^{-7}}{0{,}3166} = 2{,}2530 \times 10^{-6}$$

20) Perhitungan x pemisalan

Dalam mencari x_pemisalan ditentukan terlebih dahulu nilai α = 10 - 100 dan nilai r = 3 - 9. Kemudian nilai x_pemisalan dihitung dengan rumus sebagai berikut : $\sim x^r + x - c = 0$

a) Tingkat 1 / *Base Isolation*

$10\,x^3 + x - 7{,}13205 \times 10^{-7} = 0$

Dicari melalui persamaan Newton Raphson, sehingga didapatkan nilai:

$x = 2{,}2530 \times 10^{-6}$

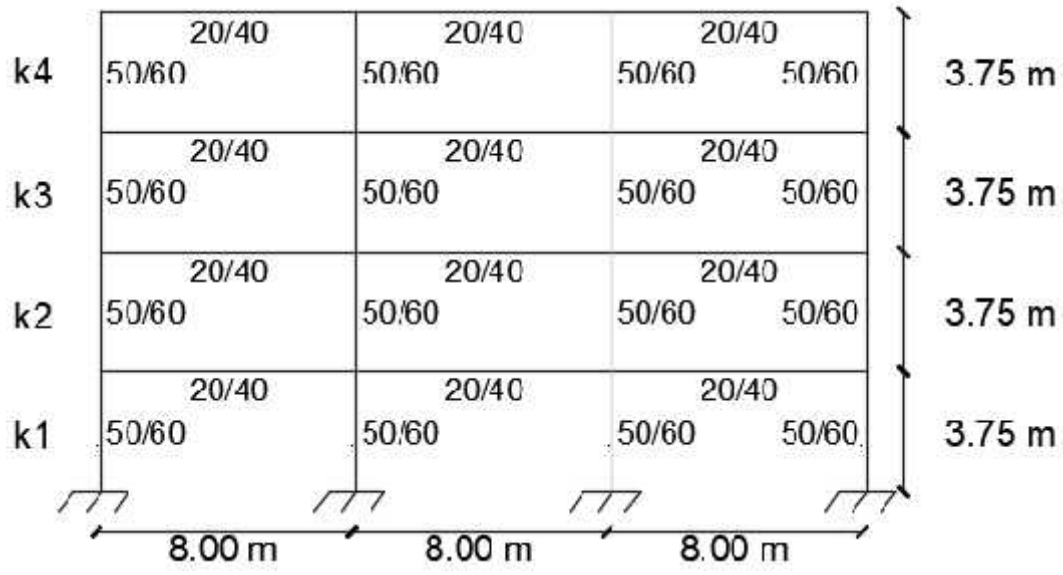
21) Perhitungan tegangan geser tiap Tingkat (τ)

a) Tingkat 1 / *Base Isolation*

$\tau_0 = 7{,}1709\ kg/cm^2 \times 2{,}2530 \times 10^{-6} = 1{,}61563 \times 10^{-5}\ kg/cm^2$

Untuk langkah selanjutnya dimulai dari persamaan matriks kekakuan yang baru dan perhitungan seterusnya sama seperti perhitungan sebelumnya.

B. Perhitungan manual struktur 4 tingkat tanpa isolasi dasar (Tipikal)



Dimana diketahui data struktur dan data isolasi dasar:

f. Data Struktur,

q lantai = 2800 kg/m’

q atap = 2000 kg/m’

f’c = 25 Mpa

1. Perhitungan Berat (W) Tiap – Tiap Tingkat

$W_1 = panjang \times q$

$= (8\ m + 8\ m + 8\ m) \times 2800\ kg\ /\ m'$

$= 67200\ \ kg$

$W_2 = panjang \times q$

$= (8\ m + 8\ m + 8\ m) \times 2800\ kg\ /\ m'$

$= 67200\ \ kg$

$W_3 = panjang \times q$

$= (8\ m + 8\ m + 8\ m) \times 2800\ kg\ /\ m'$

$= 67200\ \ kg$

$W_4 = panjang \times q$

$= (8\ m + 8\ m + 8\ m) \times 2000\ kg\ /\ m'$

$= 48000\ \ kg$

Berat total struktur,

$W = W_1 + W_2 + W_3 + W_4$

$= 67200\ \ kg + 67200\ \ kg + 67200\ \ kg + 48000\ \ kg$

$= 249600\ \ kg$

2. Perhitungan Massa (m) Tiap – Tiap Tingkat

$$m_1 = \frac{W_1}{g} = \frac{67200\ kg}{980\ cm/dt^2} = 68{,}5714\ kg\,dt^2/cm$$

$$m_2 = \frac{W_2}{g} = \frac{67200\ kg}{980\ cm/dt^2} = 68{,}5714\ kg\,dt^2/cm$$

$$m_3 = \frac{W_3}{g} = \frac{67200\ kg}{980\ cm/dt^2} = 68{,}5714\ kg\,dt^2/cm$$

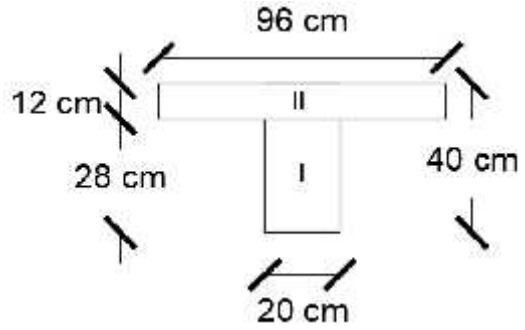
$$m_4 = \frac{W_4}{g} = \frac{48000\ kg}{980\ cm/dt^2} = 48{,}9796\ kg\,dt^2/cm$$

3. Menghitung Momen Inersia Potongan

$$I_{c1} = \frac{1}{12} \times b \times h^3 = \frac{1}{12} \times 50cm \times 60^3 cm = 900000\ cm^4$$

$$I_{c1} = I_{c2} = I_{c3} = I_{c4}$$

Inertia balok T,



$$A_1 = b_1 \times h_1 = 20\ cm \times 28\ cm = 560\ cm^2$$

$$A_2 = b_2 \times h_2 = 96\ cm \times 12\ cm = 1152\ cm^2$$

$$y_1 = \frac{(ht - tp)}{2} = \frac{(40\ cm - 12\ cm)}{2} = 14\ cm$$

$$y_2 = ht - \frac{tp}{2} = 40\ cm - \frac{12\ cm}{2} = 34\ cm$$

$$y = \frac{A_1 \times y_1 + A_2 \times y_2}{A_1 + A_2} = \frac{(560\ cm^2 \times 14\ cm) + (1152\ cm^2 \times 34\ cm)}{560\ cm^2 + 1152\ cm^2}$$

$$= 27{,}4579\ cm$$

$$I_1 = \frac{1}{12} \times b_1 \times {h_1}^3 + A_1 \times (y - y_1)^2$$

$$= \frac{1}{12} \times 20\ cm \times 28^3\ cm + 560\ cm^2 \times (27{,}4579\ cm - 14\ cm)^2$$

$$= 138011{,}7694\ cm^4$$

$$I_2 = \frac{1}{12} \times b_2 \times {h_2}^3 + A_2 \times (y - y_2)^2$$

$$= \frac{1}{12} \times 96\ cm \times 12^3\ cm + 1152\ cm^2 \times (27{,}4579\ cm - 34\ cm)^2$$

$$= 63127{,}8693\ cm^4$$

$$I_b = I_1 + I_2 = 138011{,}7694\ cm^4 + 63127{,}8693\ cm^4 = 201139{,}6387\ cm^4$$

$$I_{b1} = I_{b2} = I_{b3}$$

4. Perhitungan Kekakuan Kolom Jepit-Jepit (Kj)

$$k_{c1} = \frac{12 \times E \times I}{L_1^{\,3}} = \frac{12 \times 4700\sqrt{25}\ MPa \times 10.2 \times 900000\ cm}{375^3\ cm} = 49090{,}56\ kg/cm$$

$$k_{c1} = k_{c2} = k_{c3} = k_{c4}$$

Kekakuan total,

$$K_j = k_{c1} + k_{c2} + k_{c3} + k_{c4}$$

$$= 49090{,}56 + 49090{,}56 + 49090{,}56 + 49090{,}56 = 196362{,}24\ kg/cm$$

5. Perhitungan Kekakuan dengan Cara Muto (Km)

a. Besaran EI/L

$$\frac{E \times I_{c1}}{L_{c1}} = \frac{4700\sqrt{25}\ MPa \times 10.2 \times 900000\ cm^4}{375\ cm} = 575280000\,cm^3$$

$$\frac{E \times I_{c1}}{L_{c1}} = \frac{E \times I_{c2}}{L_{c2}} = \frac{E \times I_{c3}}{L_{c3}} = \frac{E \times I_{c4}}{L_{c4}}$$

$$\frac{E \times I_{b1}}{L_{b1}} = \frac{4700\sqrt{25}\ MPa \times 10.2 \times 201139{,}6387\ cm^4}{800\ cm} = 60266464{,}2243 cm^3$$

$$\frac{E \times I_{b1}}{L_{b1}} = \frac{E \times I_{b2}}{L_{b2}} = \frac{E \times I_{b3}}{L_{b3}}$$

b. Nilai k

Diambil nilai konstanta K=575280000 cm³ maka,

$$k_{c1} = \frac{575280000 cm^3}{575280000 cm^3} = 1$$

$$k_{c1} = k_{c2} = k_{c3} = k_{c4}$$

$$k_{b1} = \frac{60266464{,}2243 cm^3}{575280000 cm^3} = 0{,}10476$$

$$k_{b1} = k_{b2} = k_{b3}$$

c. Nilai Cm

1) Koefisien kekakuan kolom tepi

$$C_{m1} = \frac{\sum k_{ba} + 0{,}5k_c}{\sum k_{ba} + 2k_c} = \frac{0{,}10476 + 0.5 \times 1}{0{,}10476 + 2 \times 1} = 0{,}28733$$

$$C_{m2} = \frac{\sum k_{bi}}{\sum k_{bi} + 4k_c} = \frac{0{,}10476 + 0{,}10476}{(0{,}10476 + 0{,}10476) + 4 \times 1} = 0{,}04977$$

$$C_{m2} = C_{m3} = C_{m4}$$

2) Koefisien kekakuan kolom tengah

$$C_{m1} = \frac{\sum k_{ba} + 0{,}5k_c}{\sum k_{ba} + 2k_c} = \frac{(0{,}10476 + 0{,}10476) + 0.5 \times 1}{(0{,}10476 + 0{,}10476) + 2 \times 1} = 0{,}32112$$

$$C_{m2} = \frac{\sum k_{bi}}{\sum k_{bi} + 4k_c} = \frac{2 \times (0{,}10476 + 0{,}10476)}{2 \times (0{,}10476 + 0{,}10476) + 4 \times 1} = 0{,}09483$$

$$C_{m2} = C_{m3} = C_{m4}$$

d. Kekakuan Kolom Total

$$K_m = C_m \times k_c$$

$$K_{m1} = 2 \times (0.28733 + 0{,}32112) \times 49090{,}56 = 59738{,}2444\ kg/cm$$

$$K_{m2} = 2 \times (0.04977 + 0{,}09482) \times 49090{,}56 = 14196{,}9126\ kg/cm$$

$$K_{m2} = K_{m3} = K_{m4}$$

6. Rekapitulasi Massa (m) dan Kekakuan (k) Struktur

a. Massa

$$m_1 = 68{,}5714\ kg\, dt^2/cm$$

$$m_2 = 68{,}5714\ kg\, dt^2/cm$$

$$m_3 = 68{,}5714\ kg\ dt^2/cm$$

$$m_4 = 48{,}9796\ kg\, dt^2/cm$$

b. Kekakuan

$$k_1 = 59738{,}2444\ kg\ /\ cm$$

$$k_2 = 14196{,}9126\ kg\ /\ cm$$

$$k_3 = 14196{,}9126\ kg\ /\ cm$$

$$k_4 = 14196{,}9126\ kg\ /\ cm$$

7. Perhitungan Mode Shapes

Matriks massa

$$[M]=\begin{bmatrix} m1 & 0 & 0 & 0 \\ 0 & m2 & 0 & 0 \\ 0 & 0 & m3 & 0 \\ 0 & 0 & 0 & m4 \end{bmatrix}$$

$$[M]=\begin{bmatrix} 68{,}5714 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 48{,}9796 \end{bmatrix}$$

Matriks kekakuan

$$[K]=\begin{bmatrix} k1+k2 & -k2 & 0 & 0 \\ -k2 & k2+k3 & -k3 & 0 \\ 0 & -k3 & k3+k4 & -k4 \\ 0 & 0 & -k4 & k4 \end{bmatrix}$$

$$[K]=\begin{bmatrix} 73935{,}157 & -14196{,}913 & 0 & 0 \\ -14196{,}913 & 28393{,}825 & -14196{,}913 & 0 \\ 0 & -14196{,}913 & 28393{,}825 & -14196{,}913 \\ 0 & 0 & -14196{,}913 & 14196{,}913 \end{bmatrix}$$

Apabila digunakan unit massa (m) = 68,5714 kg dt^2/cm dan unit kekakuan (k) = 14196,913 kg/cm, maka matriks massa tanah (m) dan matriks kekakuan tanah (k) diatas dapat ditulis kembali :

$$[M]=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0{,}7143 \end{bmatrix}$$

$$[K]=\begin{bmatrix} 5{,}2078 & -1 & 0 & 0 \\ -1 & 2 & -1 & 0 \\ 0 & -1 & 2 & -1 \\ 0 & 0 & -1 & 1 \end{bmatrix}$$

Dengan demikian dapat disusun persamaan *Eigen Problem* sebagai berikut

$$\begin{bmatrix} 5{,}2078-\alpha & -1 & 0 & 0 \\ -1 & 2-\alpha & -1 & 0 \\ 0 & -1 & 2-\alpha & -1 \\ 0 & 0 & -1 & 1-0{,}7143\alpha \end{bmatrix}.\begin{Bmatrix} \phi 1 \\ \phi 2 \\ \phi 3 \\ \phi 4 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

Kemudian persamaan – persamaan diatas dapat ditulis menjadi bentuk yang lebih sederhana seperti diberikan dibawah ini,

$$(5{,}2078-\alpha).\phi_1 - \phi_2 = 0$$

$$-\phi_1 + (2-\alpha).\phi_2 - \phi_3 = 0$$

$$-\phi_2 + (2-\alpha).\phi_3 - \phi_4 = 0$$

$$-\phi_3 + (1-0{,}7143\alpha).\phi_4 = 0$$

Dengan mengambil nilai $\phi_1 = 1$ yang selanjutnya nilai tersebut di distribusikan ke persamaan diatas, dengan metode distribusi aljabar biasa maka nilai mode yang lainnya dapat dicari. Hasilnya adalah sebagai berikut.

$$[\phi] = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 5{,}0043 & 3{,}6149 & 1{,}9163 & -0{,}3119 \\ 7{,}9899 & 0{,}4716 & -3{,}4749 & 0{,}0981 \\ 9{,}3493 & -3{,}4229 & 2{,}5719 & -0{,}0333 \end{bmatrix}$$

Selanjutnya dapat dihitung nilai frekuensi sudut (ω) tiap Tingkat sebagai berikut ini,

$$\alpha_1 = 0{,}1454 \quad \rightarrow \quad \mu_1 = \sqrt{\alpha_1.\frac{k}{m}} = \sqrt{0{,}1454.\frac{14196{,}913}{68{,}5714}} = 6{,}4917\ \frac{rad}{dt}$$

$$\alpha_2 = 1{,}1378 \quad \rightarrow \quad \mu_2 = \sqrt{\alpha_2.\frac{k}{m}} = \sqrt{1{,}1378.\frac{14196{,}913}{68{,}5714}} = 18{,}1602\ \frac{rad}{dt}$$

$$\alpha_3 = 2{,}3511 \quad \rightarrow \quad \mu_3 = \sqrt{\alpha_3.\frac{k}{m}} = \sqrt{2{,}3511.\frac{14196{,}913}{68{,}5714}} = 26{,}1052\ \frac{rad}{dt}$$

$$\alpha_4 = 3{,}9427 \quad \rightarrow \quad \mu_4 = \sqrt{\alpha_4.\frac{k}{m}} = \sqrt{3{,}9427.\frac{14196{,}913}{68{,}5714}} = 33{,}8055\ \frac{rad}{dt}$$

8. Kontrol Dengan Kondisi Partisipasi Mode :

   a. Untuk mode ke – 1

$$P_1 = \{\phi\}_1^T.[M]\{I\}$$

$$P_1 = \begin{bmatrix} 1 & 5{,}0043 & 7{,}9899 & 9{,}3493 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$

$$P_1 = 1417{,}5274$$

$$M_1 = \{\text{¤}\}_1^T . [M] \{\text{¤}_1\}$$

$$M_1 = \begin{bmatrix} 1 & 5{,}0043 & 7{,}9899 & 9{,}3493 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 5{,}0043 \\ 7{,}9899 \\ 9{,}3493 \end{bmatrix}$$

$$M_1 = 10444{,}5870$$

Partisipasi untuk mode ke – 1 : $\Gamma_1 = \dfrac{P_1}{M_1} = \dfrac{1417{,}5274}{10444{,}5970} = 0.1357$

b. Untuk mode ke – 2

$$P_2 = \{\text{¤}\}_2^T . [M] \{I\}$$

$$P_2 = \begin{bmatrix} 1 & 3{,}6149 & 0{,}4716 & -3{,}4229 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$

$$P_2 = 181{,}1394$$

$$M_2 = \{\text{¤}\}_2^T . [M] \{\text{¤}_2\}$$

$$M_2 = \begin{bmatrix} 1 & 3{,}6149 & 0{,}4716 & -3{,}4229 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 3{,}6149 \\ 0{,}4716 \\ -3{,}4229 \end{bmatrix}$$

$$M_2 = 1553{,}7647$$

Partisipasi untuk mode ke – 2 : $\Gamma_2 = \dfrac{P_2}{M_2} = \dfrac{181{,}1394}{1553{,}7647} = 0{,}1166$

c. Untuk mode ke – 3

$$P_3 = \{\text{¤}\}_3^T . [M] \{I\}$$

$$P_3 = \begin{bmatrix} 1 & 1{,}9163 & -3{,}4749 & 2{,}5719 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$

$$P_3 = 87{,}6594$$

$$M_3 = \{\phi\}_3^T . [M] \{\phi_3\}$$

$$M_3 = \begin{bmatrix} 1 & 1{,}9163 & -3{,}4749 & 2{,}5719 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1{,}9163 \\ -3{,}4749 \\ 2{,}5719 \end{bmatrix}$$

$$M_3 = 1472{,}3987$$

Partisipasi untuk mode ke – 3 : $\Gamma_3 = \dfrac{P_3}{M_3} = \dfrac{87{,}6594}{1472{,}3987} = 0{,}0595$

d. Untuk mode ke – 4

$$P_4 = \{\phi\}_4^T . [M] \{I\}$$

$$P_4 = \begin{bmatrix} 1 & -0{,}3119 & 0{,}0981 & -0{,}0333 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$

$$P_4 = 52{,}2730$$

$$M_4 = \{\phi\}_4^T . [M] \{\phi_4\}$$

$$M_4 = \begin{bmatrix} 1 & -0{,}3119 & 0{,}0981 & -0{,}0333 \end{bmatrix} \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ -0{,}3119 \\ 0{,}0981 \\ -0{,}0333 \end{bmatrix}$$

$$M_4 = 75{,}9599$$

Partisipasi untuk mode ke – 4 : $\Gamma_4 = \dfrac{P_4}{M_4} = \dfrac{52{,}2730}{75{,}9599} = 0{,}6882$

Sebagai kontrol bahwa jumlah partisipasi mode harus sama dengan satu, maka

$$\sum \Gamma = \Gamma_1 + \Gamma_2 + \Gamma_3 + \Gamma_4$$

$$= 0{,}1357 + 0{,}1166 + 0{,}0595 + 0{,}6882$$

$$= 1 \qquad \text{(memenuhi syarat)}$$

9. Perhitungan Matriks Redaman (C)

Dalam analisis digunakan matriks redaman dengan metode *Mass and Stiffness Proportional Damping* dengan nilai redaman (ξ) = 0,05

Frekuensi sudut yang akan dijadikan referensi (ω_i) diambil pada mode ke – 3 yaitu 26,1052 rad/dt dan (ω_j) pada mode ke -1 yaitu 6,4917 rad/dt.

$$= \frac{2(\P_j.\mu_j - \P_i.\mu_i)}{\mu_j^2 - \mu_i^2} = \frac{2(0,05.26,1052 - 0,05.6,4917)}{26,1052^2 - 6,4917^2} = 0,0031$$

$$\sim = 2.\P_j.\mu_j - \quad .\mu_j^2 = 2.0,05.26,1052 - 0,0031.26,1052^2 = 0,5199$$

Matriks redaman :

$$[C] = \sim.[M] + \quad .[K]$$

$$\sim.[M] = 0,5199.\begin{bmatrix} 68,5714 & 0 & 0 & 0 \\ 0 & 68,5714 & 0 & 0 \\ 0 & 0 & 68,5714 & 0 \\ 0 & 0 & 0 & 48,9796 \end{bmatrix} +$$

$$.[K] = 0,0031\begin{bmatrix} 73935,157 & -14196,913 & 0 & 0 \\ -14196,913 & 28393,825 & -14196,913 & 0 \\ 0 & -14196,913 & 28393,825 & -14196,913 \\ 0 & 0 & -14196,913 & 14196,913 \end{bmatrix}$$

Maka nilai matrik redaman [C] adalah :

$$[C] = \begin{bmatrix} 262,4659 & -43,5529 & 0 & 0 \\ -43,5529 & 122,7554 & -43,5529 & 0 \\ 0 & -43,5529 & 122,7554 & -43,5529 \\ 0 & 0 & -43,5529 & 69,0169 \end{bmatrix}$$

10. Integrasi Langsung *β-Newmark*

a. Mencari kekakuan efektif ($\hat{K}$)

Dalam mencari kekakuan efektif ditentukan terlebih dahulu nilai γ = 0,50 dan nilai β = 0,25. Kemudian nilai kekakuan efektif dihitung dengan rumus sebagai berikut :

$$\hat{K} = [K] + \left\{ \frac{¥}{\times \Delta t} \times [C] \right\} + \left\{ \frac{1}{\times \Delta t^2} \times [M] \right\}$$

$$\hat{K} = \left[\left[\begin{matrix} 73935,157 & -14196,913 & 0 & 0 \\ -14196,913 & 28393,825 & -14196,913 & 0 \\ 0 & -14196,913 & 28393,825 & -14196,913 \\ 0 & 0 & -14196,913 & 14196,913 \end{matrix} \right] \right] +$$

$$\left\{ \frac{0,50}{0,25 \times 0,01} \times \left[\begin{matrix} 262,4659 & -43,5529 & 0 & 0 \\ -43,5529 & 122,7554 & -43,5529 & 0 \\ 0 & -43,5529 & 122,7554 & -43,5529 \\ 0 & 0 & -43,5529 & 69,0169 \end{matrix} \right] \right\} +$$

$$\left\{ \frac{1}{0,25 \times \left(0,01^2\right)} \times \left[\begin{matrix} 68,5714 & 0 & 0 & 0 \\ 0 & 68,5714 & 0 & 0 \\ 0 & 0 & 68,5714 & 0 \\ 0 & 0 & 0 & 48,9796 \end{matrix} \right] \right\}$$

$$\hat{K} = \left[\begin{matrix} 2869285,4805 & -22907,4966 & 0 & 0 \\ -22907,4966 & 2795802,0450 & -22907,4966 & 0 \\ 0 & -22907,4966 & 2795802,0450 & -22907,4966 \\ 0 & 0 & -22907,4966 & 1987183,9622 \end{matrix} \right]$$

b. Mencari konstanta a

$$a = \left\{ \frac{1}{\times \Delta t} \times [M] \right\} + \left\{ \frac{¥}{} \times [C] \right\}$$

$$a = \left\{ \frac{1}{0,25 \times 0,01} \times \left[\begin{matrix} 68,5714 & 0 & 0 & 0 \\ 0 & 68,5714 & 0 & 0 \\ 0 & 0 & 68,5714 & 0 \\ 0 & 0 & 0 & 48,9796 \end{matrix} \right] \right\} +$$

$$\left\{ \frac{0,50}{0,25} \times \left[\begin{matrix} 262,4659 & -43,5529 & 0 & 0 \\ -43,5529 & 122,7554 & -43,5529 & 0 \\ 0 & -43,5529 & 122,7554 & -43,5529 \\ 0 & 0 & -43,5529 & 69,0169 \end{matrix} \right] \right\}$$

$$a = \left[\begin{matrix} 27953,5032 & -87,1058 & 0 & 0 \\ -87,1058 & 27674,0822 & -87,1058 & 0 \\ 0 & -87,1058 & 27674,0822 & -87,1058 \\ 0 & 0 & -87,1058 & 19729,8705 \end{matrix} \right]$$

c. Mencari konstanta b

$$b = \left\{ \frac{1}{2\times}\times[M] \right\} + \left\{ \left(\frac{¥}{2\times} - 1 \right) \times \Delta t \times [C] \right\}$$

$$b = \left\{ \frac{1}{2\times 0{,}25} \times \begin{bmatrix} 68{,}5714 & 0 & 0 & 0 \\ 0 & 68{,}5714 & 0 & 0 \\ 0 & 0 & 68{,}5714 & 0 \\ 0 & 0 & 0 & 48{,}9796 \end{bmatrix} \right\} +$$

$$\left\{ \left(\frac{0{,}50}{2\times 0{,}25} - 1 \right) \times 0{,}01 \times \begin{bmatrix} 262{,}4659 & -43{,}5529 & 0 & 0 \\ -43{,}5529 & 122{,}7554 & -43{,}5529 & 0 \\ 0 & -43{,}5529 & 122{,}7554 & -43{,}5529 \\ 0 & 0 & -43{,}5529 & 69{,}0169 \end{bmatrix} \right\}$$

$$b = \begin{bmatrix} 137{,}1429 & 0 & 0 & 0 \\ 0 & 137{,}1429 & 0 & 0 \\ 0 & 0 & 137{,}1429 & 0 \\ 0 & 0 & 0 & 97{,}9592 \end{bmatrix}$$

d. Perhitungan Pembebanan Siklus Ke – 1 dimana i = 0

Perhitungan pembebanan menggunakan beban riwayat gempa El Centro 1940 dimana data riwayat percepatan gempanya disajikan dalam dibawah ini.

Waktu (detik)	Percepatan Gempa (cm/dt^2)
0,00	0
0,01	0
0,02	1,6954
0,03	3,3810
0.04	5,0764
0.05	6,7620
dst	dst

Dimana diketahui pada kondisi awal bahwa nilai :

Simpangan → $y_0 = 0$

Kecepatan → $\dot{y}_0 = 0$

Percepatan → $\ddot{y}_0 = 0$

1) Mencari nilai pertambahan pembebanan ($\Delta\hat{P}_i$)

$$\Delta\hat{P}_i = \left\{ \left(\ddot{y}_{b,i+1} - \ddot{y}_{b,i} \right) \times [M] \right\} + \left(a \times [\dot{y}_i] \right) + \left(b \times [\ddot{y}_i] \right)$$

$$\Delta\hat{P}_0 = \left\{ \left(\ddot{y}_{b,0+1} - \ddot{y}_{b,0} \right) \times [M] \right\} + \left([a] \times [\dot{y}_0] \right) + \left([b] \times [\ddot{y}_0] \right)$$

$$\Delta\hat{P}_0 = \left\{ \left(\ddot{y}_{b,1} - \ddot{y}_{b,0} \right) \times [M] \right\} + \left([a] \times [\dot{y}_0] \right) + \left([b] \times [\ddot{y}_0] \right)$$

$$= \left\{ (1{,}6954 - 0{,}00) \times \begin{bmatrix} 68{,}5714 \\ 68{,}5714 \\ 68{,}5714 \\ 48{,}9796 \end{bmatrix} \right\}$$

$$+ \left(\begin{bmatrix} 27953{,}5032 & -87{,}1058 & 0 & 0 \\ -87{,}1058 & 27674{,}0822 & -87{,}1058 & 0 \\ 0 & -87{,}1058 & 27674{,}0822 & -87{,}1058 \\ 0 & 0 & -87{,}1058 & 19729{,}8705 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \right)$$

$$+ \left(\begin{bmatrix} 137{,}1429 & 0 & 0 & 0 \\ 0 & 137{,}1429 & 0 & 0 \\ 0 & 0 & 137{,}1429 & 0 \\ 0 & 0 & 0 & 97{,}9592 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \right)$$

$$\Delta\hat{P}_0 = \begin{bmatrix} 116{,}2560 \\ 116{,}2560 \\ 116{,}2560 \\ 83{,}0400 \end{bmatrix}$$

2) Mencari nilai pertambahan simpangan (Δy_i)

$\hat{K}.\Delta y_i = \Delta\hat{P}_i$

$\hat{K}.\Delta y_0 = \Delta\hat{P}_0$

$$\begin{bmatrix} 2869285,4805 & -22907,4966 & 0 & 0 \\ -22907,4966 & 2795802,0450 & -22907,4966 & 0 \\ 0 & -22907,4966 & 2795802,0450 & -22907,4966 \\ 0 & 0 & -22907,4966 & 1987183,9622 \end{bmatrix} \Delta y_0 = \begin{bmatrix} 116,2560 \\ 116,2560 \\ 116,2560 \\ 83,0400 \end{bmatrix}$$

$$\Delta y_o = \begin{bmatrix} 4,08548 \times 10^{-5} \\ 4,22635 \times 10^{-5} \\ 4,22750 \times 10^{-5} \\ 4,22751 \times 10^{-5} \end{bmatrix}$$

3) Mencari nilai pertambahan kecepatan (Δy_i)

$$\Delta \dot{y}_i = \left(\frac{¥}{\times \Delta t} \times [\Delta y_i] \right) - \left(\frac{¥}{—} \times [\dot{y}_i] \right) + \left(1 - \frac{¥}{2} \right) . \Delta t . [\ddot{y}_i]$$

$$\Delta \dot{y}_0 = \left(\frac{¥}{\times \Delta t} \times [\Delta y_0] \right) - \left(\frac{¥}{—} \times [\dot{y}_0] \right) + \left(1 - \frac{¥}{2} \right) . \Delta t . [\ddot{y}_0]$$

$$\Delta \dot{y}_0 = \left(\frac{0,50}{0,25 \times 0,01} \times \begin{bmatrix} 4,08548 \times 10^{-5} \\ 4,22635 \times 10^{-5} \\ 4,22750 \times 10^{-5} \\ 4,22751 \times 10^{-5} \end{bmatrix} \right) - \left(\frac{0,50}{0,25} \times \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \right)$$

$$+ \left(1 - \frac{0,50}{2.0,25} \right) . 0,01 . \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\Delta \dot{y}_0 = \begin{bmatrix} 0,0081710 \\ 0,0084527 \\ 0,0084550 \\ 0,0084550 \end{bmatrix}$$

4) Mencari nilai pertambahan percepatan ($\Delta \ddot{y}_i$)

$$\Delta \ddot{y}_i = \left(\frac{1}{\times \Delta t^2} \times [\Delta y_i] \right) - \left(\frac{1}{\times \Delta t} \times [\dot{y}_i] \right) - \left(\frac{1}{2} \times [\ddot{y}_i] \right)$$

$$\Delta\ddot{y}_0 = \left(\frac{1}{\times \Delta t^2} \times [\Delta y_0] \right) - \left(\frac{1}{\times \Delta t} \times [\dot{y}_0] \right) - \left(\frac{1}{2} \times [\ddot{y}_0] \right)$$

$$= \left(\frac{1}{0{,}25 \times 0{,}01^2} \times \begin{bmatrix} 4{,}08548 \times 10^{-5} \\ 4{,}22635 \times 10^{-5} \\ 4{,}22750 \times 10^{-5} \\ 4{,}22751 \times 10^{-5} \end{bmatrix} \right) - \left(\frac{1}{0{,}25 \times 0{,}01} \times \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \right)$$

$$- \left(\frac{1}{2 \times 0{,}25} \times \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \right)$$

$$\Delta\ddot{y}_0 = \begin{bmatrix} 1{,}634193 \\ 1{,}690539 \\ 1{,}691000 \\ 1{,}691004 \end{bmatrix}$$

5) Maka besarnya simpangan akhir interval (y_{i+1}) adalah :

$$y_{i+1} = y_i + \Delta y_i$$

$$y_{0+1} = y_0 + \Delta y_0$$

$$y_1 = y_0 + \Delta y_0$$

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix}_{siklus\ ke-1} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 4{,}08548 \times 10^{-5} \\ 4{,}22635 \times 10^{-5} \\ 4{,}22750 \times 10^{-5} \\ 4{,}22751 \times 10^{-5} \end{bmatrix} = \begin{bmatrix} 4{,}08548 \times 10^{-5} \\ 4{,}22635 \times 10^{-5} \\ 4{,}22750 \times 10^{-5} \\ 4{,}22751 \times 10^{-5} \end{bmatrix}$$

6) Menghitung simpangan antar tingkat / *interstorey drift* (yy)

$$yy = y_i - y_{i-1}$$

a) Tingkat 1

$$yy_{11} = 4{,}08548 \times 10^{-5} - 0 = 4{,}08548 \times 10^{-5}$$

b) Tingkat 2

$$yy_{12} = 4{,}22635\times10^{-5} - 4{,}08548\times10^{-5} = 1{,}40865\times10^{-6}$$

c) Tingkat 3

$$yy_{13} = 4{,}22750\times10^{-5} - 4{,}22635\times10^{-5} = 1{,}15426\times10^{-8}$$

d) Tingkat 4

$$yy_{14} = 4{,}22751\times10^{-5} - 4{,}22750\times10^{-5} = 9{,}42655\times10^{-11}$$

jika disusun dalam bentuk matrik maka,

$$y_r = \begin{bmatrix} 4{,}08548\times10^{-5} \\ 1{,}40865\times10^{-6} \\ 1{,}15426\times10^{-8} \\ 9{,}42655\times10^{-11} \end{bmatrix}$$

7) Maka besarnya kecepatan akhir interval ($\dot{y}_{i+1}$) adalah :

$$\dot{y}_{i+1} = \dot{y}_i + \Delta\dot{y}_i$$

$$\dot{y}_{0+1} = \dot{y}_0 + \Delta\dot{y}_0$$

$$\dot{y}_1 = \dot{y}_0 + \Delta\dot{y}_0$$

$$\begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \\ \dot{y}_3 \\ \dot{y}_4 \end{bmatrix}_{siklus\ ke-1} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0{,}0081710 \\ 0{,}0084527 \\ 0{,}0084550 \\ 0{,}0084550 \end{bmatrix} = \begin{bmatrix} 0{,}0081710 \\ 0{,}0084527 \\ 0{,}0084550 \\ 0{,}0084550 \end{bmatrix}$$

8) Maka besarnya percepatan akhir interval ($\ddot{y}_{i+1}$) adalah :

$$\ddot{y}_{i+1} = \ddot{y}_i + \Delta\ddot{y}_i$$

$$\ddot{y}_{0+1} = \ddot{y}_0 + \Delta\ddot{y}_0$$

$$\ddot{y}_1 = \ddot{y}_0 + \Delta\ddot{y}_0$$

$$\begin{bmatrix} \ddot{y}_1 \\ \ddot{y}_2 \\ \ddot{y}_3 \\ \ddot{y}_4 \end{bmatrix}_{siklus\ ke-1} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 1{,}634193 \\ 1{,}690539 \\ 1{,}691000 \\ 1{,}691004 \end{bmatrix} = \begin{bmatrix} 1{,}634193 \\ 1{,}690539 \\ 1{,}691000 \\ 1{,}691004 \end{bmatrix}$$

9) Menghitung rasio simpangan antar tingkat / *interstorey drift ratio* (yr)

$$yr = \frac{yy_i}{h} \times 100$$

a) Tingkat 1

$$yr_1 = \frac{4{,}08548 \times 10^{-5}}{375} \times 100 = 1{,}08946 \times 10^{-5}\%$$

b) Tingkat 2

$$yr_2 = \frac{1{,}40865 \times 10^{-6}}{375} \times 100 = 3{,}75639 \times 10^{-7}\%$$

c) Tingkat 3

$$yr_3 = \frac{1{,}15426 \times 10^{-8}}{375} \times 100 = 3{,}07802 \times 10^{-9}\%$$

d) Tingkat 4

$$yr_4 = \frac{9{,}42655 \times 10^{-11}}{375} \times 100 = 2{,}51375 \times 10^{-11}\%$$

10) Menghitung gaya horizontal tingkat (F)

$$F = y_i \times [K]$$

$$F = \begin{bmatrix} 4{,}08548 \times 10^{-5} \\ 4{,}22635 \times 10^{-5} \\ 4{,}22750 \times 10^{-5} \\ 4{,}22751 \times 10^{-5} \end{bmatrix} \times \begin{bmatrix} 73935{,}157 & -14196{,}913 & 0 & 0 \\ -14196{,}913 & 28393{,}825 & -14196{,}913 & 0 \\ 0 & -14196{,}913 & 28393{,}825 & -14196{,}913 \\ 0 & 0 & -14196{,}913 & 14196{,}913 \end{bmatrix}$$

$$= \begin{bmatrix} 2{,}420597 \\ 0{,}019835 \\ 0{,}000163 \\ 1{,}3383 \times 10^{-6} \end{bmatrix} \text{kg}$$

11) Menghitung gaya geser tingkat (V)

$$V = \sum_{j=i}^{n} F_j$$

a) Tingkat 1

$$V_1 = F_1 + F_2 + F_3 + F_4$$

$$= 2{,}420597 + 0{,}019835 + 0{,}000163 + 1{,}3383 \times 10^{-6}$$

$= 2{,}440595$ kg

b) Tingkat 2

$V_2 = F_2 + F_3 + F_4$

$= 0{,}019835 + 0{,}000163 + 1{,}3383 \times 10^{-6}$

$= 0{,}019998$ kg

c) Tingkat 3

$V_3 = F_3 + F_4$

$= 0{,}000163 + 1{,}3383 \times 10^{-6}$

$= 0{,}000164$ kg

d) Tingkat 4

$V_4 = F_4$

$= 1{,}3383 \times 10^{-6}$ kg

12) Menghitung momen guling (Mg)

$$M_g = \sum_{j=i}^{n} F_j \times H_j$$

a) Dasar

$M_{g0} = (F_1 \times H_1) + (F_2 \times H_2) + (F_3 \times H_3) + (F_4 \times H_4)$

$= 2{,}440595 \times 375 + 0{,}019998 \times 375 + 0{,}000164 \times 375$

$+ 1{,}3383 \times 10^{-6} \times 375$

$= 915{,}22327$ kg.cm

b) Tingkat 1

$M_{g1} = (F_2 \times H_2) + (F_3 \times H_3) + (F_4 \times H_4)$

$= 0{,}019998 \times 375 + 0{,}000164 \times 375 + 1{,}3383 \times 10^{-6} \times 375$

$= 7{,}499416$ kg.cm

c) Tingkat 2

$M_{g2} = (F_3 \times H_3) + (F_4 \times H_4)$

$= 0{,}000164 \times 375 + 1{,}3383 \times 10^{-6} \times 375$

$= 0{,}061451$ kg.cm

d) Tingkat 3

$M_{g3} = (F_4 \times H_4)$

$= 1{,}3383 \times 10^{-6} \times 375$

$= 0{,}000502$ kg.cm

e) Tingkat 4

$M_{g4} = 0$ kg.cm

Untuk langkah selanjutnya dimulai dari persamaan matriks kekakuan yang baru dan perhitungan seterusnya sama seperti perhitungan sebelumnya.