COMPUTER ANALYSIS OF R. C. COUPLED SHEAR WALLS

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1. Introduction

The method described earlier in this issue* has been applied to develop a computer program in ALGOL 60 language for the computer ODRA 1024 of the Technical University, Budapest. Principal characteristics and application possibilities of this program will be presented.

2. Computer program based on the compatibility method

2.1. *General*

Deformation equations written for each storey permit to vary the geometry and structural data for each storey, much extending the range of applicability beyond that of continuous model methods. In case of high storey numbers, however, great many data have to be stored and handled. Therefore the program is composed of an organizing program and segment procedures. Input and computed data are stored in the background. Except for some parameters, procedures contact each other and the organizing program only through the background. Thereby the medium-size computer available permitted to analyze walls with relatively high storey numbers (up to about 35). The running time — with printing — was 3 min for a ten-storey wall, and 6 min for a 16-storey wall.

2.2. *Input data*

Part of the input data are parameters operating different program branches — depending on their value — and computation parts with alternative assumptions such as:

* Matuscsák, T.: Analysis of Reinforced Concrete Coupled Shear Walls. Per. Pol. Arch. 19 (1975) 3—4.

— Wind load:
  a) actual;
  b) concentrated force for each storey from standard uniform load;
  c) variable as specified in standard.
— Eccentricity of vertical loads:

a) moments due to eccentric forces acting on each higher storey are separately considered for each wall strip;

b) like a) but the sum of the two moments is distributed between the wall strips according to the ratio of inertiae;

c) only moment of the eccentric force acting on the storey over the tested one is considered.

— Theoretical connecting beam span:
  a) bay width;
  b) 1.15 times the bay width.
— Connecting beam cross section:
  a) without reduction;
  b) reduced for the shear deformation.

Further data describe wall loads, geometry and structural characteristics for each storey. It is worth mentioning that also vertical reinforcement in wall sections can be indicated as a percentage of concrete cross section, and so can be the tensile and compressive reinforcement cross section in the connecting beams.

Loads:
- horizontal concentrated forces acting at the floor midline (wind loads, horizontal forces due to placing inaccuracies);
- vertical, concentrated forces of given eccentricity acting on the wall strips each storey (permanent working loads on the floor, dead load);
- uniform vertical load on the connecting beam (permanent working load on, and dead load of the floor).

2.3. *Functioning of the program*

To suit the method of solution, the problem consists in:
- computation of the unit factors of wall strips and connecting beams and of the load constants;
- establishment and solution of the deformational equation system;
- in knowledge of the shear forces, determination of the final stress distribution and of the deformational condition.

The procedure will be outlined in a flow chart needing the definition of variable S to be understood.

2.3.1. *Iteration for the cracking of connecting beams.* The description of the computation procedure already referred to the practical occurrence of connecting beam cracking, accompanied by stiffness loss, and change of connecting beam unit factors. Therefore after computing in the elastic range ($S = 2$) and printing the output, unit factors of connecting beams found to be cracked are recomputed. The entrained variation of the deformational equation system affects coefficient matrix elements along the principal diagonal alone. Shear forces obtained by re-solving the equation system characterize the cracked condition, computation is, however, repeated from the modification of the connecting beam unit factors until vector differences between two consecutive outputs are below a specified limit, or up to a specified maximum of iterations. Numerical examples available show the procedure to rapidly converge, after three or four iterations the deviation is less than the limit of 5 kp for each storey.

2.3.2. *Computation of connecting beam unit factors.* Connecting beam unit factors express the magnitude of the vertical relative displacement between two beam ends upon the effect of 1 Mp of shear force. The point of inflection is assumed at mid-span.

Computation of the unit factor:

a) in the elastic range:

— by the Mohr method, the connecting beam is considered as a bar of constant cross section restrained both ends.

b) after cracking:

— moments from uniform vertical load and shear force in the connecting beam are summarized, then sections cracked under positive and negative moments told apart. The unit factor is determined by considering the connecting beams as bars of variable cross section (I_1, I_{2N}, I_{2P}) restrained both ends;

— in conformity with Hungarian Standard MSZ 15023/71, the cracked connecting beams are accounted for in stress state II, with constant inertia throughout their length. Otherwise, the procedure is the same as in the elastic range.

2.4. *Outputs*

Computer outputs for both elastic and cracked range include:

— vertical relative displacement components of connecting beam ends;

— wall strip and connecting beam stresses in each storey;

— horizontal displacements of the wall strip; and

— concrete and steel stresses in the restrained cross sections of the connecting beams and in the wall strip cross sections clamped in the foundation.

3. Residual problems

Computation of the cracked connecting beam stiffness is only an approximation. A more exact computation would require a method involving material properties of reinforced concrete, and its influencing factors, based on test results. Also for wall strips, an exacter computation method — better approximating the physical reality — would result from the closer consideration of the shear deformation of wall strips, of the effect of horizontal reinforcement, of the appearance of cracks.

4. Example, notations

Let us see now some output details of a problem as an example. Interpretation of data sheet symbols: Numerals 1 and 2 refer to the left or right-hand restraint of connecting beams, or to the left- or right-side wall strip, to the sense. For notations of this kind, only one of both will be defined.

MZ (mpm): sum of bending moments in the two wall cross sections due to vertical loads;
MY (mpm): bending moment due to horizontal load;
MGZ (mpm): bending moment in both fixed ends of the connecting beams due to uniform load;
NZ1 (mp): axial force in the left-side wall cross section due to vertical load;
MREPHP (mpm): positive cracking moment in the connecting beam cross section;
MREPHN (mpm): negative cracking moment in the connecting beam cross section;
QREPHP (mp): shear force belonging to MREPHP;
QREPHN (mp): shear force belonging to MREPHN;
QH (mp): ultimate shear force of the connecting beam;
ZGREPH (mp/m): uniform load superimposed to a given shear force, cracking the connecting beam top fibre;
MGQ1 (mpm): moment in the left-side clamped cross section due to the shear force;
SZG1 (kp/sq.cm): concrete stress in the compressed extreme fibre of the left-side clamped cross section;
SZGV1 (kp/sq.cm): tensile steel stress of the left-side clamped beam cross section;
N1 (Mp): final axial force in the left-side wall cross sections;
M1F, m1A (mpm): final bending moments developing above and below the restraint in the left-side wall;
MQ (mpm): sum of bending moments in walls due to shear forces;
ETAG (mm): vertical relative displacement of connecting beam ends, equal to the relative displacement of the corresponding sections of wall strips due to bending moments from horizontal and vertical loads, and to axial forces;
ETAY (mm): horizontal displacement of the wall strips due to horizontal and vertical loads, and to shear forces;
Substituent solid cantilever: one for which the work done by horizontal load would equal that for the coupled shear walls.
FAA (sq.cm): bottom reinforcement in the connecting beam;
FAF (sq.cm): top reinforcement in the connecting beam;
E_{b0} (kp/sq-cm): concrete modulus of elasticity under short-term loads;
E_{bt} (kp/sq.cm): concrete modulus of elasticity under long-term loads;
E_a (kp/sq.cm): reinforcement modulus of elasticity;
σ_{bH} (kp/sq.cm): ultimate concrete compressive stress;
σ_{bh} (kp/sq.cm): ultimate concrete tensile stress;
σ_{aH} (kp/sq.cm): ultimate reinforcement stress.

EXAMPLE

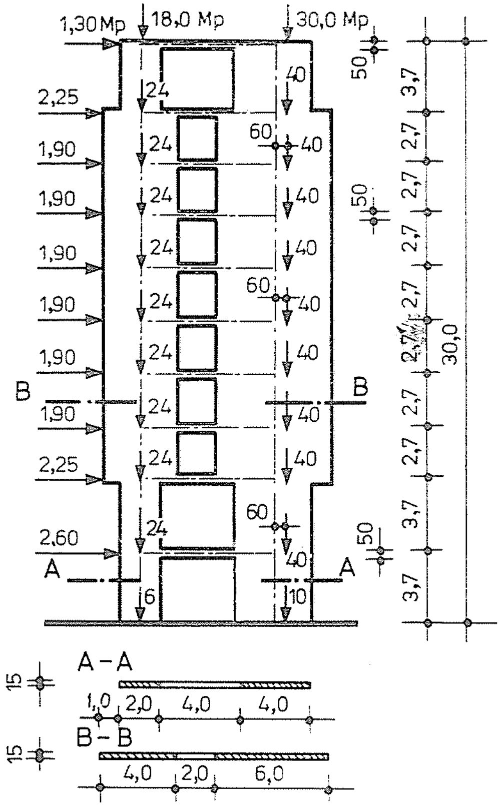

Fig. 1.

I. Input

Running storey:

E_{bo} = 200 000 kp/cm²
E_{bt} = 110 000 kp/cm²
E_a = 2 100 000 kp/cm²
σ_{bH} = 140 kp/cm²
σ_{bh} = 13 kp/cm²
σ_{aH} = 3 400 kp/cm²
FAA = FAF = 7.62 cm²

Initial stresses: (mpm, mp)

Storey	MZ	MY	MGZ	NZ1	NZ2
10	54.00	.00	.00	− 18.00	− 30.00
9	78.00	4.81	.00	− 42.00	− 70.00
8	102.00	14.38	.00	− 66.00	−110.00
7	126.00	29.07	.00	− 90.00	−150.00
6	150.00	48.87	.00	−114.00	−190.00
5	174.00	73.00	.00	−138.00	−230.00
4	198.00	103.84	.00	−162.00	−270.00
3	222.00	139.00	.00	−186.00	−310.00
2	246.00	179.28	.00	−210.00	−350.00
1	270.00	242.78	.00	−234.00	−390.00
0	276.00	315.90	.00	−240.00	−400.00

Connecting beam cross section data: (mpm, mp, mp/m)

Storey	MREPHP	MREPHN	QREPHP	QREPHN	QH	ZGREPH
10	1.545	−1.545	.772	.772	5.289	.000
9	1.545	−1.545	1.545	1.545	10.579	.000
8	1.545	−1.545	1.545	1.545	10.579	.000
7	1.545	−1.545	1.545	1.545	10.579	.000
6	1.545	−1.545	1.545	1.545	10.579	.000
5	1.545	−1.545	1.545	1.545	10.579	.000
4	1.545	−1.545	1.545	1.545	10.579	.000
3	1.545	−1.545	1.545	1.545	10.579	.000
2	1 545	−1.545	.772	.772	5.289	.000
1	1.545	−1.545	.772	.772	5.289	.000

II. A. Outputs for the elastic range

Connecting beam strains and stresses: (mpm, kp/cm²)

Storey	MGQ1	MGQ2	SZG1	SZG2	SZGV1	SZGV2
10	3.71	− 3.71	−31.22	−31.22	524.45	524.45
9	7.20	− 7.20	−60.55	−60.55	1017.31	1017.31
8	6.78	− 6.78	−57.07	−57.07	958.79	958.79
7	6.85	− 6.85	−57.63	−57.63	968.25	968.25
6	7.30	−7.30	−61.44	−61.44	1032.23	1032.23
5	8.11	− 8.11	−68.26	−68.26	1146.81	1146.81
4	9.31	− 9.31	−78.39	−78.39	1316.97	1316.97
3	11.02	−11.02	−92.70	−92.70	1557.44	1557.44
2	3.71	− 3.71	−31.26	−31.26	525.20	525.20
1	2.99	− 2.99	−25.20	−25.20	423.35	423.35

Wall strip stresses: (mp, mpm)

Storey	N1	N2	M1F	M1A	M2F	M2A	MQ
10	− 16.15	− 31.85	+ 6.00	+ 4.56	+ 48.00	+36.46	− 12.98
9	− 32.95	− 79.05	+15.96	+ 4.45	+ 53.86	−15.01	− 63.35
8	− 50.17	−125.83	+12.12	+ 1.27	+ 40.91	+ 4.29	−110.82
7	− 67.32	−172.68	+10.11	− .84	+ 34.13	− 2.85	−158.76
6	− 84.02	−219.98	+ 9.17	− 2.51	+ 30.94	− 8.48	−209.87
5	− 99.91	−268.09	+ 8.67	− 4.31	+ 29.26	−14.54	−266.65
4	−114.59	−317.41	+ 8.04	− 6.86	+ 27.15	−23.15	−331.85
3	−127.58	−368.42	+ 6.66	−10.96	+ 22.48	−37.00	−408.96
2	−149.72	−410.28	+ 1.81	+ 3.37	+ 14.50	+ 2.94	−421.97
1	−172.22	−451.78	+10.09	+ 8.93	+ 80.73	+71.41	−432.45
0	−178.22	−461.78	+17.72	+ .00	+141.74	+ .00	−432.45

Relative displacement components of beam ends: (mm)

Storey	ETAMY	ETAMZ	ETANZ	ETAMQ	ETANG	ETAG
10	+15.35	+21.19	+.50	−30.30	−3.59	+3.14
9	+15.29	+19.46	+.47	−29.96	−3.56	+1.69
8	+15.24	+19.02	+.49	−29.65	−3.50	+1.59
7	+15.13	+18.46	+.52	−29.11	−3.39	+1.61
6	+14.94	+17.78	+.56	−28.33	−3.24	+1.71
5	+14.64	+16.98	+.61	−27.30	−3.03	+1.90
4	+14 21	+16.07	+.67	−25.99	−2.77	+2.19
3	+13.61	+15.04	+.75	−24.36	−2.45	+2.58
2	+12.83	+13.89	+.83	−22.35	−2.05	+3.14
1	+ 7.31	+ 7.14	+.44	−11.31	−1.04	+2.53
0	+ .00	+ .00	+.00	+ .00	+ .00	+ .00

Horizontal displacement components (mm); deflection angle from the vertical (rad)

Storey	ETAYY	ETAYZ	ETAYQ	ETAY	FI
10	+54.63	+62.21	−101.45	+15.40	$4.49\cdot10^{-4}$
9	+46.53	+51.98	− 85.52	+13.00	$2.41\cdot10^{-4}$
8	+40.64	+44.86	− 74.02	+11.48	$2.27\cdot10^{-4}$
7	+34.79	+37.91	− 62.69	+10.01	$2.30\cdot10^{-4}$
6	+28.99	+31.17	− 51.61	+ 8.55	$2.45\cdot10^{-4}$
5	+23.28	+24.70	− 40.88	+ 7.10	$2.72\cdot10^{-4}$
4	+17.72	+18.53	− 30.61	+ 5.64	$3.12\cdot10^{-4}$
3	+12.35	+12.72	− 20.90	+ 4.17	$3.69\cdot10^{-4}$
2	+ 7.25	+ 7.30	− 11.89	+ 2.67	$4.49\cdot10^{-4}$
1	+ 1.93	+ 1.87	− 2.99	+ .81	$3.62\cdot10^{-4}$
0	+ .00	+ .00	+ .00	+ .00	$.00\cdot10^{-4}$

Foundation clamping stresses: (kp/cm²)

SZ11 = −41.69 SZ12 = −77.12 SZ23 = −41.53 SZ24 = −112.40

Width of the substituting solid cantilever: 8.72 m

II. B. Outputs taking cracking into account

Connecting beam stiffness in stress states I and II: (mm/mp)

Storey	DQ1	DQ2
10	1.693	2.659
9	.235	.377
8	.235	.377
7	.235	.377
6	.235	.378
5	.235	.378
4	.235	.378
3	.235	.378
2	1.693	2.660
1	1.693	2.592

Connecting beam shear forces in stress states I and II: (mp)

Storey	I	II	III	no change after the second iteration
10	1.85	1.60	1.60	
9	7.20	7.28	7.28	
8	6.78	7.01	7.01	
7	6.85	7.05	7.05	
6	7.30	7.36	7.36	
5	8.11	7.89	7.89	
4	9.31	8.64	8.64	
3	11.02	9.62	9.62	
2	1.86	1.55	1.55	
1	1.50	1.18	1.18	

Connecting beam strains and stresses: (mpm, kp/cm²)

Storey	MGQ1	MGQ2	SZG1	SZG2	SZGV1	SZGV2
10	3.20	−3.20	30.06	−30.06	985.76	985.76
9	7.28	−7.28	68.42	−68.42	2244.20	2244.20
8	7.01	−7.01	65.86	−65.86	2160.05	2160.05
7	7.05	−7.05	66.30	−66.30	2174.46	2174.46
6	7.36	−7.36	69.17	−69.17	2268.75	2268.75
5	7.89	−7.89	74.16	−74.16	2432.30	2432.40
4	8.64	−8.64	81.21	−81.21	2663.47	2663.47
3	9.62	−9.62	90.46	−90.46	2967.08	2967.08
2	3.10	−3.10	29.13	−29.13	955.56	955.56
1	2.36	−2.36	22.16	−22.16	726.92	726.92

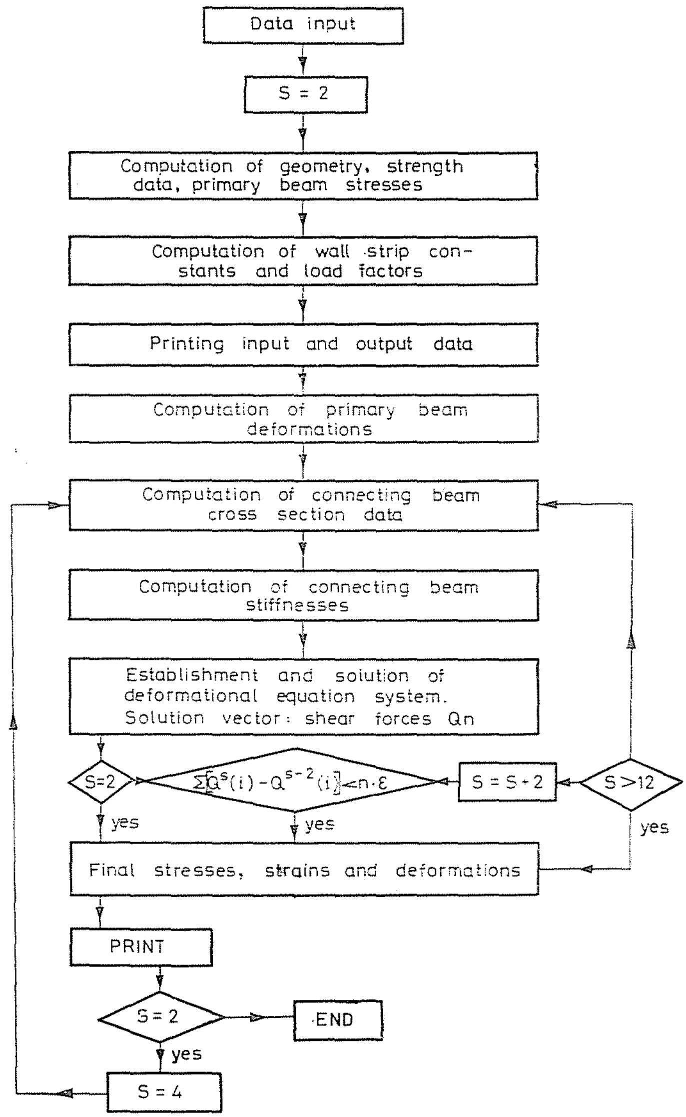
Data input
S = 2
Computation of geometry, strength data, primary beam stresses
Computation of wall strip constants and load factors
Printing input and output data
Computation of primary beam deformations
Computation of connecting beam cross section data
Computation of connecting beam stiffnesses
Establishment and solution of deformational equation system. Solution vector: shear forces Qn
S=2
Σ[Q^s(i) - Q^{s-2}(i)] < n·ε
S = S + 2
S > 12
yes
yes
yes
Final stresses, strains and deformations
PRINT
S = 2
END
yes
S = 4

Fig. 2.

Wall strip stresses: (mp, mpm)

Storey	N1	N2	M1F	M1A	M2F	M2A	MQ
10	− 16.40	− 31.60	+ 6.00	+ 4.76	+ 48.00	+38.05	− 11.19
9	− 33.12	− 78.88	+16.37	+ 4.72	+ 55.25	+15.94	− 62.14
8	− 50.12	−125.88	+12.40	+ 1.19	+ 41.84	+ 4.00	−111.19
7	− 67.06	−172.94	+10.03	− 1.26	+ 33.85	− 4.24	−160.56
6	− 83.70	−220.30	+ 8.76	− 3.02	+ 29.56	−10.18	−212.07
5	− 99.82	−268.18	+ 8.17	− 4.46	+ 27.56	−15.04	−267.29
4	−115.18	−316.82	+ 7.90	− 5.93	+ 26.65	− 20.00	−327.77
3	−129.55	−366.45	+ 7.60	− 7.80	+ 25.64	−26.33	−395.13
2	−152.00	408.00	+ 3.35	+ 2.14	+ 26.79	+17.15	−405.98
1	−174.82	−449.18	+11.87	+10.95	+ 94.93	+87.60	−414.23
0	−180.82	−459.18	+19.74	+ .00	+157.93	+ .00	−414.23

Relative displacement components of beam ends: (mm)

Storey	ETAMY	ETAMZ	ETANZ	ETAMQ	ETANQ	ETAG
10	+15.35	+21.19	+.50	−29.29	−3.49	+4.25
9	+15.29	+19.46	+.47	−29.00	−3.47	+2.75
8	+15.24	+19.02	+.49	−28.69	−3.41	+2.64
7	+15.13	+18.46	+.52	−28.15	−3.30	+2.66
6	+14.94	+17.78	+.56	−27.36	−3.14	+2.78
5	+14.64	+16.98	+.61	−26.32	−2.94	+2.98
4	+14.21	+16.07	+.67	−25.01	−2.67	+3.27
3	+13.61	+15.04	+.75	−23.40	−2.36	+3.64
2	+12.83	+13.89	+.83	−21.46	−1.97	+4.12
1	+ 7.31	+ 7.14	+.44	−10.84	−1.00	+3.05
0	+ .00	+ .00	+.00	+ .00	+ .00	+ .00

Horizontal displacement components (mm), deflection angle from the vertical (rad):

Storey	ETAYY	ETAYZ	ETAYQ	ETAY	FI
10	+54.63	+62.21	−97.84	+19.01	$6.070 \cdot 10^{-4}$
9	+46.53	+51.98	−82.43	+16.08	$3.930 \cdot 10^{-4}$
8	+40.65	+44.86	−71.30	+14.20	$3.780 \cdot 10^{-4}$
7	+34.79	+37.91	−60.34	+12.35	$3.800 \cdot 10^{-4}$
6	+28.99	+31.17	−49.64	+10.52	$3.970 \cdot 10^{-4}$
5	+23.28	+24.70	−39.28	+ 8.70	$4.260 \cdot 10^{-4}$
4	+17.72	+18.53	−29.39	+ 6.86	$4.670 \cdot 10^{-4}$
3	+12.35	+12.72	−20.05	+ 5.02	$5.200 \cdot 10^{-4}$
2	+ 7.25	+ 7.30	−11.40	+ 3.16	$5.890 \cdot 10^{-4}$
1	+ 1.93	+ 1.87	− 2.86	+ .93	$4.360 \cdot 10^{-4}$
0	+ .00	+ .00	+ .00	+ .00	$.000 \cdot 10^{-4}$

Foundation clamping stresses: (kp/cm^2)

SZ11 = −40.53 SZ12 = −80.02 SZ23 = −37.05 SZ24 = −116.01

Width of the substituting solid cantilever: 8.14 m

Summary

A computer program for reinforced concrete coupled shear walls is presented. Its functioning is illustrated in a sketchy flow chart. The suggested method involves iteration of the deformational equation system for taking the connecting beam cracking into consideration. A fraction of the outputs is shown in the example concluding the paper.

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