Design Analysis of Semi-Rigid Frames: Evaluation and Implementation

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ABSTRACT

The evaluation of the major assumptions, procedures, and proposed models associated with the simplified analysis procedure for unbraced flexible frames is presented. The highlights of this procedure, as well as numerical examples, are also discussed. The implementation of flexible frame analysis and design on personal computers is demonstrated.

1. INTRODUCTION

A simplified procedure for the analysis of unbraced flexible frames was introduced in Ref. 3. The procedure is largely based on the philosophy of the so-called B_1 and B_2 amplification factor method recommended by the AISC/LRFD Specification.[1] While the amplification factor method is designed for elastic rigid frames, the simplified analysis procedure suggests a number of modifications to accommodate the presence of flexible connections. These include: two linearized moment-rotation relationships (expressed by R_{ko} and R_{kb}) for modeling the connection behavior and a modified relative stiffness factor (G') for determining the effective length of elastically restrained columns. The modified initial stiffness (R_{ko}) is considered for implementation in the first-order analysis of the nonsway frame configuration which produces M_{nt} moments. The secant stiffness R_{kb} is designed for implementation in the first-order analysis of the sway frame which yields M_{nt} moments. The design moment of member is then determined by the equation

$$M_u = B_1 M_{nt} + B_2 M_{lt} \tag{1.1}$$

Herein, the evaluation of the major assumptions and proposed connection models, as well as the overall analysis procedure, is presented. Moreover, the implementation of the amplification factor method and the simplified analysis procedure on personal computers is demonstrated.

2. MOMENT-ROTATION CURVES AND CONNECTION PARAMETERS

The idealized connection models are developed on the basis of connection M-θ_r curves which, in turn, are formulated on either experimental or analytical basis.[2] For practical implementations, the power model by Kishi, et al.[7] is used here for the development of the simplified linear connection models (R_{ko} and R_{kb}). As a good representative of the semi-rigid type of connections, the top- and seat-angle with double web-angle connection is used here and in subsequent sections. For this type of connection, the following expressions are used for determining the initial stiffness (R_{ki}), ultimate moment (M_u) and M-θ_r relationship.

$$R_{ki} = \frac{3(EI_t)d_1^2}{g_1(g_1^2 + 0.78t_t^2)} + \frac{6(EI_a)d_3^2}{g_3(g_3^2 + 0.78t_a^2)} \tag{2.1}$$

$$M_u = M_{os} + M_{pt} + V_{pt}d_2 + 2V_{pa}d_4 \tag{2.2}$$

$$M = \frac{R_{ki}\theta_r}{[1 + (\theta_r/\theta_o)^n]^{1/n}} \tag{2.3}$$

where

EI_a and EI_t	are bending stiffnesses of the leg of web-angle and top-angle adjacent to the column face, respectively
d_i and g_i	are dimensional characteristics of connection
M_{os}	plastic moment in the seat-angle
M_{pt}	plastic moment in the top-angle
V_{pt}	plastic shear force in the top-angle
V_{pw}	the resultant of plastic shear force in a single web-angle

As can be seen, the power model allows for depicting two of the most important connection characteristics: the initial stiffness (R_{ki}) and the ultimate moment (M_u). These are the two quantities on which the modified initial stiffness R_{ko}[3] is based. Since M_u and R_{ki} are developed on an analytical basis, a comparison with actual values determined experimentally is necessary to validate their use.

2.1 Ultimate Moment of Connection

A computer program was developed[2] to determine the analytical values of the initial stiffness and ultimate moment of connection. Connection test data from Data Base of Steel Beam-to-Column Connections[6] is used here in the comparative study. In particular, data for the type top- and seat-angle with double web-angle connections is utilized. All 22 experimental sets of data available for this type are compared with the analytical results. It is assumed that the tests were

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terminated when the connection reached its ultimate moment capacity.

Figure 1 shows the ultimate moment values determined experimentally with those determined analytically by Eq. 2.2. It can be seen that the analytical expression gives very good estimates of the actual moment capacity of connection. It should be noted, however, that most of the relatively large discrepancies (connections 19, 20, and 22) are due to the fact that these are partially welded connections whereas the analytical model is based on an all-bolted connection setup.

2.2 Initial Stiffness of Connection

It is well known that the determination of the exact initial connection stiffness is a difficult task even by experimental means. This is because connection stiffness differs considerably during the initial stages of loading, and in a test case this is reflected by the first few readings of the test. To demonstrate this, connection tangential stiffness at the first five test readings of several different connections is shown in Table 1. These values were taken within the initial 10% of connection moment capacity.

For comparison purposes, the average of the tangential connection stiffness at the first four experimental readings[6] is considered. This value is compared with the initial stiffness determined by Eq. 2.1. This is shown in Fig. 2. Considering the diversity of the real connection stiffness obtained from experimental tests, the scatter graph presents an acceptable agreement between the experimental and analytical stiffness values for the connections shown in this figure.

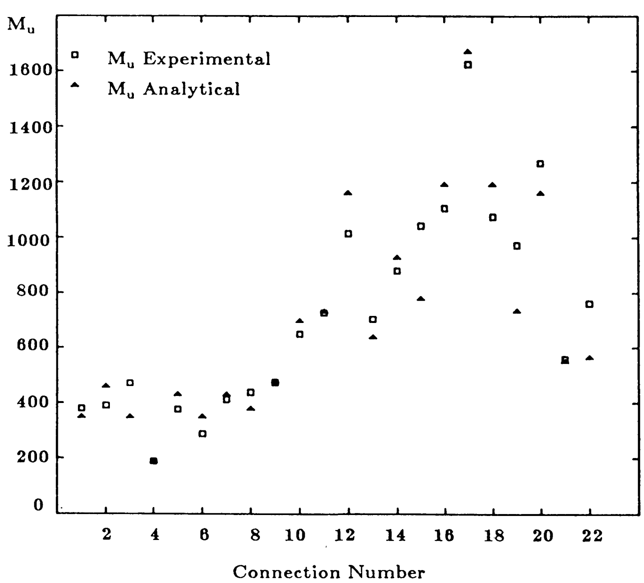

Fig. 1. Comparison of ultimate connection moment between experimental data and analytical predictions.

Table 1.
Tangent Stiffness Corresponding to the First Five Test Readings of Connection Moment (Kishi and Chen, 1986)

Connection Number	Test Reading No. 1	2	3	4	5
III-7	49,370	47,530	44,340	41,000	38,180
III-8	57,290	61,630	58,940	54,380	47,510
III-9	107,300	103,900	93,130	80,160	68,960
III-10	58,250	466,400	347,500	229,500	157,900
III-11	299,000	238,900	180,900	152,500	130,300
III-12	435,600	325,300	205,700	165,800	145,400
III-13	165,300	111,600	97,710	95,770	90,150
III-14	208,900	222,800	198,000	161,600	115,400

3. IDEALIZED CONNECTION MODELS

3.1 Modified Initial Connection Stiffness (R_{ko})

In the simplified analysis procedure,[3] the modified initial stiffness (R_{ko}) is used to represent the average connection behavior during the first stages of loading. In the analysis of unbraced frames, according to this procedure, R_{ko} is used in a first-order analysis of the nonsway configuration of frame subjected to loads causing no lateral sway to determine M_{nt} moments. This section attempts to illustrate how the modified initial stiffness complies with the purpose of its usage.

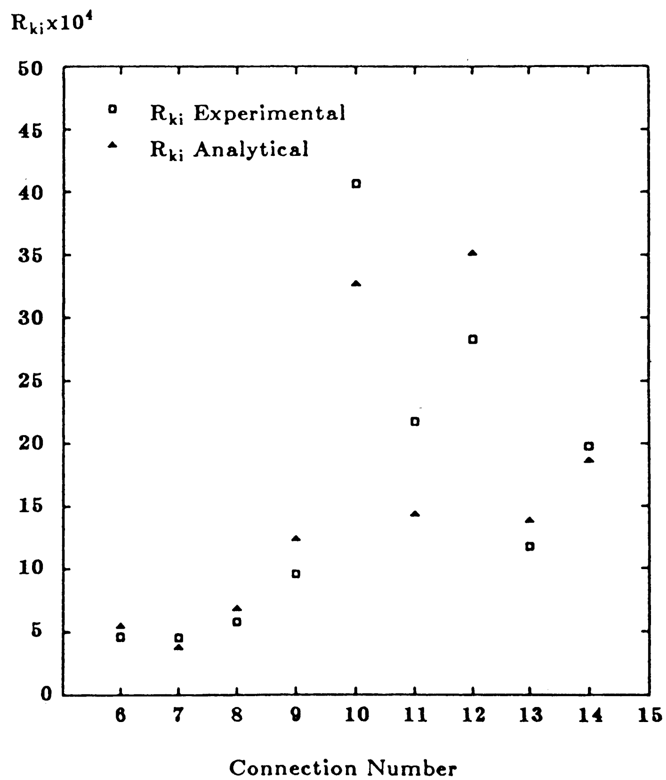

Fig. 2. Comparison of initial connection stiffness between experimental data and analytical predictions.

For this purpose, and for further numeric evaluations, a number of frame-connection combinations are used. The frames are labeled FR-1, FR-2, FR-3, FR-4, and FR-5 and are shown in Figs. 3, 4, 5, and 6. The variety of frame configurations is chosen as such to ensure, in part, different end conditions for the columns. It also covers a range of frame dimensions, number of spans and stories, member sections, and load proportions. Four connections[6] labeled III-11, III-14, III-16, and III-17 are implemented in the analysis of these frames. All connections are of type top- and seat-angle with double web angles, and the M–θ_r curves (Fig. 7) are selected as such to represent the range of stiffness where connection behavior is considered semi-rigid.

A comparative analysis is conducted using all five frames and implementing each of the four semi-rigid connections. Exact second-order elastic analysis (with actual connection curves) is conducted using sequential loading. Gravity loads are applied in the first loading sequence, the horizontal loads are then added as the second loading sequence. A sample of the comparative study is presented here.

The results of the two approaches of analysis (using connections III-16) are plotted in Fig. 8. It can be seen that the use of the modified initial stiffness helps predict the overall flexible frame behavior expressed by moment distribution in the members very closely, which may lead to the conclusion that R_{ko} can be used to represent the average connection behavior as suggested by the simplified analysis procedure.

3.2 Connection Stiffness by Beam-Line (R_{kb})

This stiffness is implemented in the first-order analysis of the unbraced frame[3] subjected to loads causing lateral sway. This

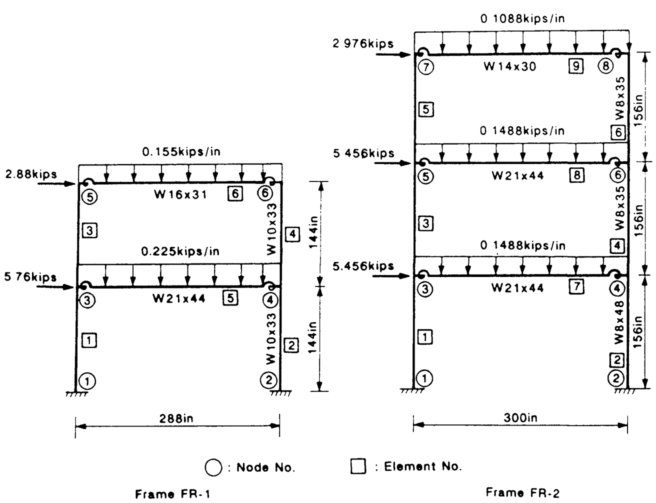

Fig. 3. Partially restrained frames FR-1 and FR-2

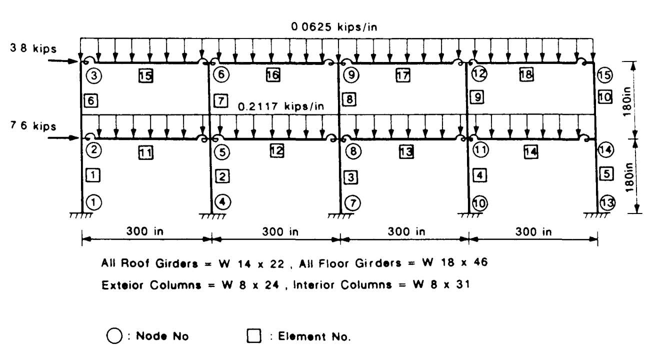

Fig. 4. Partially restrained frame FR-3.

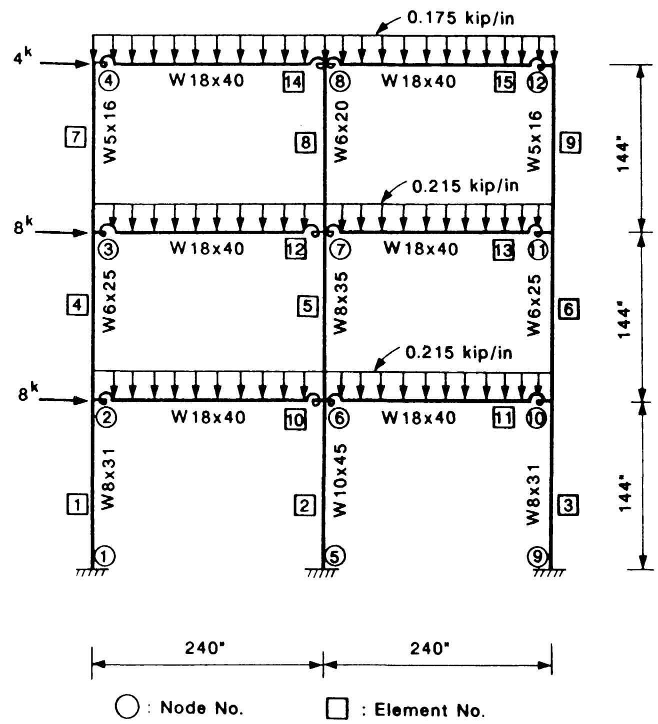

Fig. 5. Partially restrained frame FR-4.

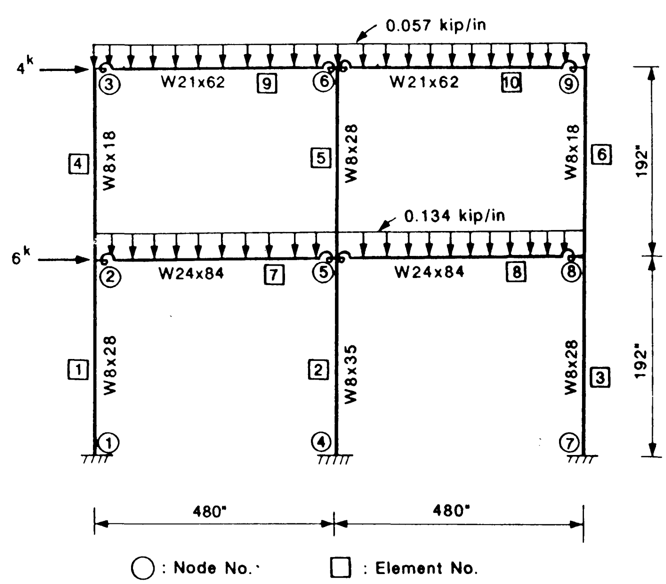

Fig. 6. Partially restrained frame FR-5

produces column moments M_{lt}. The use of this stiffness is presumed to approximate the average real connection behavior at advanced stages of loading which correspond, according to the simplified analysis procedure, to the application of lateral loads after all gravity loadings have taken place.

Thus, to get a feeling of how connection stiffness R_{kb} performs in such a role, two types of analysis are performed using the same frame-connection combinations of Sec. 3.1. First, an exact second-order analysis using actual connection curves is performed for load sequence 2 (loads causing lateral sway) which allows the determination of column moments M_{exact}. Secondly, a first-order analysis of the same frame and load configuration is performed implementing connection stiffness R_{kb} which gives column moments M_{lt}. The results of these analyses are presented in Fig. 9.

It can be seen that the use of connection stiffness R_{kb} allows to predict, with a sufficient degree of accuracy, the behavior of flexible frames expressed by the moment distribution in frame columns.

4. MORE NUMERIC EVALUATIONS

The same frame configurations and connections described in Sec. 3.1 are used here in a numerical study aimed at illustrating the proposed method of analysis and rationalizing its approach. In this study, exact second-order and linear first-order analysis were conducted using the computer program FLFRM.[5] Exact analysis which accounts for second-order effects was conducted with the actual nonlinear M–θ_r curve of the connection. As mentioned earlier, the first-order analysis was conducted according to the loading arrangement associated with B_1 and B_2 method[3] and implementing connection stiffness R_{ko} or R_{kb} as applicable. A number of

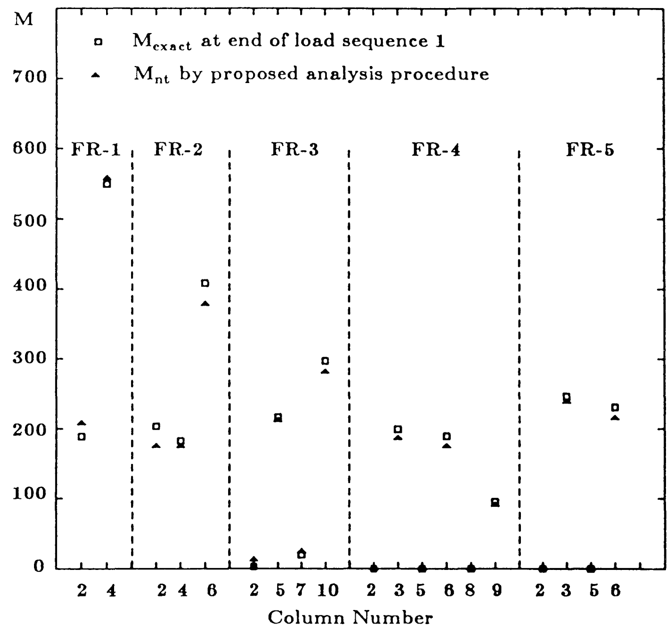

Fig. 8. Comparison of column moments due to nonsway loads in frames with the more rigid connection III-16.

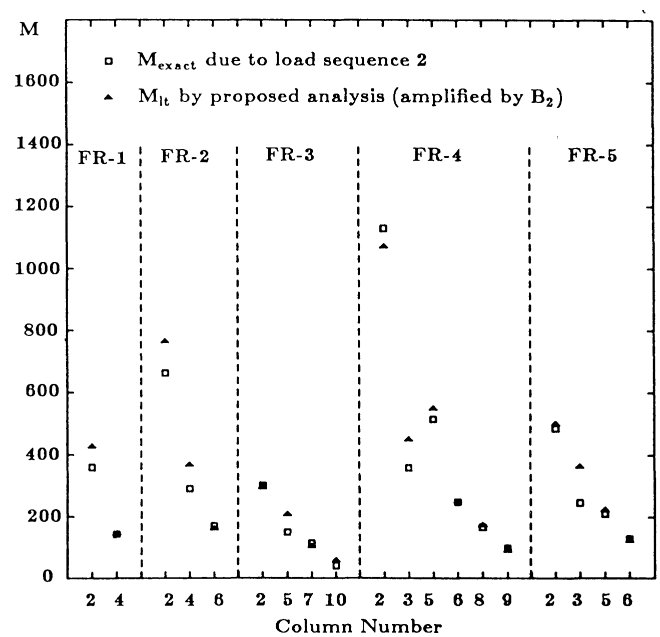

Fig. 9. Comparison of column moments due to sway loads in frames with the more rigid connection III-16.

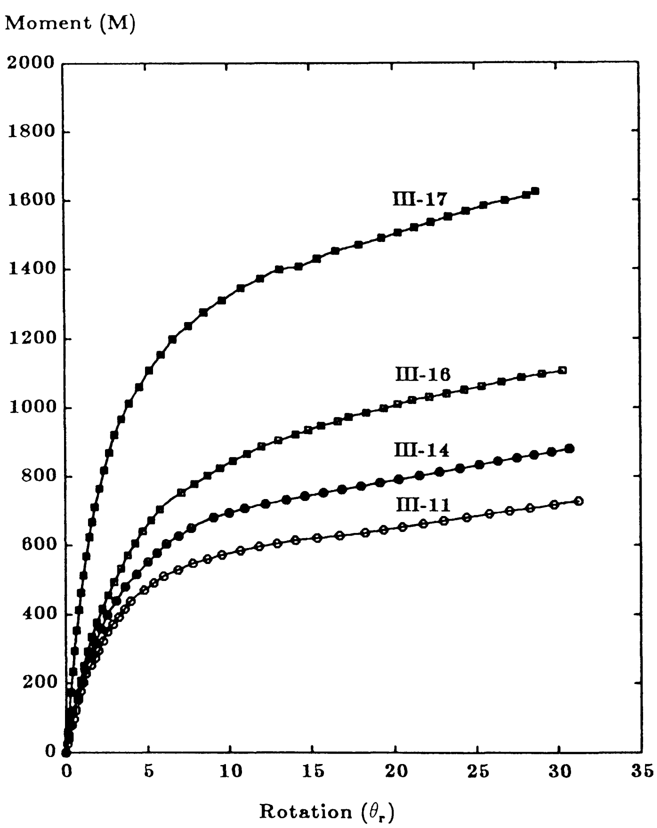

Fig. 7. Experimental connection curves (Kishi and Chen, 1986).

Table 2.
Moment Values Determined by Proposed (M_u) and Exact (M_{exact}) Analyses (Connection III-16 Is Used)

Frame Code		M_u	M_{exact}	M_u/M_{exact}
FR-1	Col. 2	-636	-543	1.170
(Fig. 3)	Col. 4	-704	-691	1.020
FR-2	Col. 2	-988	-891	1.109
	Col. 4	-604	-522	1.156
(Fig. 3)	Col. 6	-596	-611	0.976
FR-3	Col. 2	-308	-302	1.03
	Col. 5	-420	-369	1.137
	Col. 7	-128	-133	0.968
(Fig. 4)	Col. 10	-341	-337	1.009
FR-4	Col. 2	-1072	-1102	0.973
	Col. 3	-637	-559	1.139
	Col. 5	-551	-512	1.076
	Col. 6	-427	-430	0.993
	Col. 8	-174	-166	1.047
(Fig. 5)	Col. 9	-182	-186	0.978
FR-5	Col. 2	-501	-484	1.035
	Col. 3	-603	-505	1.196
	Col. 5	-225	-210	1.071
(Fig. 6)	Col. 6	-339	-354	0.959

combinations of connections and frames are utilized to illustrate the versatility of the proposed method. The results of analysis are presented in a tabulated form. It is worth mentioning that the related tables include not only the maximum column moment of each floor but all moments that control the design of all columns in those floors where different member sizes are used.

Table 2 shows moment values of column members (M_{exact}) for all five frames determined by exact second-order analysis using connection III-16, as well as moment values (M_u) determined by the simplified analysis procedure.[3] It can be seen that the simplified procedure offers very good predictions for the design column moments in these frames. Table 3 contains the normalized (by exact solution, i.e., M_{exact}) column moments in frame FR-5. As can be seen, all four connections (III-11, III-14, III-16, and III-17) were used in the analysis. It is evident from these tables that the predictions of the design column moments by the proposed method of analysis are very good and generally conservative for most members. The unconservative moment values (all of which happened to occur in top floor columns) are considered to be within the allowable tolerance in engineering practice (less than 5%). In addition, these values represent, in most cases, better estimates than those obtained by the conventional rigid frame analysis as will be shown later.

The selection of a different, and at the same time softer, connection stiffness (i.e., R_{ko}) as opposed to the initial stiffness (R_{ki}) was based on parametric calculations which showed that the performance of R_{ko} is more adequate for the simplified method of analysis. A sample of data supporting this suggestion is presented in Table 4 which was generated with the implementation of connection III-17. The table shows the results of the exact (second-order with real connection curve) and simplified methods of analysis. The simplified analysis was conducted with two different combinations of the idealized connection stiffnesses: The first combination uses R_{ki} and R_{kb} in a first-order analysis to determine M_{nt} and M_{lt}, respectively. The second combination uses R_{ko} and R_{kb} in a similar analysis.

It can be seen that the design moments M_u determined by using R_{ko} for the calculation of M_{nt} are closer to the exact solution than those obtained by using R_{ki}. This can be

Table 3.
Design Moments M_u in FR-5 Normalized by Exact Solution M_{exact} (See Fig. 6)

Connection Used (Fig. 7)	Normalized Design Moment			
	Col. 2	Col. 3	Col. 5	Col. 6
Connection III-11	0.993	1.209	1.083	0.950
Connection III-14	1.107	1.187	1.073	0.952
Connection III-16	1.035	1:196	1.071	0.959
Connection III-17	1.084	1.053	1.112	0.966

Table 4.
Analysis Results for Moments M_{nt} and M_{lt} Using Combinations of R_{ki} and R_{ko} with R_{kb} for Linear Models of Connection III-17

Frame Code	Column No.	Analysis with R_{ki} and R_{kb}			Analysis with R_{ko} and R_{kb}			Exact Analysis
		M_{nt}	M_{lt}	M_u	M_{nt}	M_{lt}	M_u	
FR-1	2	343	372	728	290	372	678	547
(Fig. 3)	4	707	134	844	654	134	792	798
FR-2	2	315	659	1002	280	659	969	835
	4	307	359	683	268	359	648	595
(Fig. 3)	6	522	139	663	492	139	634	653
FR-3	2	42	251	317	29	251	307	284
	5	239	177	434	236	177	432	424
	7	56	92	150	42	92	137	133
(Fig. 4)	10	311	53	365	306	53	361	377
FR-4	2	00	1027	1086	00	1027	1092	1113
	3	218	433	676	216	433	677	601
	5	00	538	584	00	538	591	553
	6	189	243	453	193	243	461	486
	8	00	168	184	00	168	184	177
(Fig. 5)	9	85	88	181	91	88	187	193
FR-5	2	00	424	462	00	424	468	431
	3	268	311	606	271	311	613	583
	5	00	201	208	00	201	210	188
(Fig. 6)	6	231	112	348	236	112	353	366

explained by examining the values of M_{nt} which are computed by implementing these stiffness values. As compared to R_{ko}, the higher stiffness R_{ki} causes larger moments to be allocated at beam ends which are, consequently, transferred to column ends. It is evident that the modified initial stiffness R_{ko} is a more adequate and reasonable choice for the simplified analysis as opposed to the initial stiffness R_{ki}.

5. FRAME ANALYSIS ON PERSONAL COMPUTERS

One of the main objectives of the simplified analysis procedure[3] was to establish a simple and practical analysis procedure for the design of steel frames with semi-rigid connections. In this section, attempt is made to provide for even more efficient implementations of flexible frame analysis. The use of personal computers for the analysis and design process is sought.

In today's world, it is necessary to take advantage of the spreading use of personal computers and related software. Thus, analysis methods that are simple in principle must also be accompanied with equally simple and efficient practical implementation as well. For the problem at hand (B_1 and B_2 concept of analysis), the number of variables, quantities, and operations involved is quite large and their determination is a time-consuming process. For example, the quantities and properties that need to be evaluated for each compression member in a frame are listed below in ascending sequence of their dependency and course of calculation. They are symbolically expressed as in the tables and figures associated with this section.

A. For rigid frames:

E = modulus of elasticity

I = moment of inertia of member

L = length of member

$G_a = \dfrac{\Sigma\left(\dfrac{EI}{L}\right)_c}{\Sigma\left(\dfrac{EI}{L}\right)_b}$, restraint factor at column end A

$G_b = \dfrac{\Sigma\left(\dfrac{EI}{L}\right)_c}{\Sigma\left(\dfrac{EI}{L}\right)_b}$, restraint factor at column end B

$K(B_1)$ = nonsway effective length factor, used for the determination of B_1

$K(B_2)$ = sway effective length factor, used for the determination of B_2

$P_{ek}(B_1) = \pi^2 EI/(KL)^2$, in which $K = K(B_1)$

$P_{ek}(B_2) = \pi^2 EI/(KL)^2$, in which $K = K(B_2)$

M_1 = smaller end moment in member

M_2 = larger end moment in member

$C_m = 0.6 - 0.4\left(\dfrac{M_1}{M_2}\right)$

P_u = compression axial force in member

$B_1 = \dfrac{C_m}{1 - \dfrac{P_u}{P_{ek}}} \geq 1.0$, P–δ amplification factor

$B_2 = \dfrac{1}{1 - \dfrac{\Sigma P_u}{\Sigma P_{ek}}}$, P–Δ amplification factor

M_{nt} = moment in member due to nonsway loads

M_{lt} = moment in member due to sway loads

$M_u = B_1 M_{nt} + B_2 M_{lt}$, design moment

B. For flexible frames:

In addition to all the quantities mentioned above, the proposed analysis procedure for flexible frames[3] requires the following values:

R_{ko} = modified initial stiffness for each connection

R_{kb} = secant connection stiffness determined by beam-line

I'_o = modified moment of inertia of beam which accounts for connection stiffness R_{ko} at its end

I'_b = modified moment of inertia of beam which accounts for connection stiffness R_{kb} at its end

$\bar{\alpha}_{nt} = \dfrac{\Sigma I_b}{\Sigma (I'_{nt})_b}$, scaling factor for the nonsway relative stiffness factor G

$\bar{\alpha}_{lt} = \dfrac{\Sigma I_b}{\Sigma (I'_{lt})_b}$, scaling factor for the sway relative stiffness factor G

$G'_a = \bar{\alpha} G_a$, modified relative stiffness factor at column end A

$G'_b = \bar{\alpha} G_b$, modified relative stiffness factor at column end B

It is clear that the evaluation of these quantities for a frame with even a small number of beam and column members is voluminous and time-consuming. An efficient format for their evaluation is very much needed. The utilization of personal computers along with popular and inexpensive software programs is now presented.

5.1 Implementation with Spreadsheet Programs

It is fair to say that personal computers as well as certain types of software programs (like spreadsheet and integrated software) are available in almost every business, consulting, or design office. It would be of great advantage if such software programs were employed to serve as analysis tools in the design process at minimal effort and no additional cost. The analysis of frames, rigid as well as flexible, using B_1 and B_2 method is presented in a spreadsheet format which is found to be very efficient and easy to implement.

Table 5.
Analysis of Semi-Rigid Frames in Spreadsheet Format

		G'_a	G'_b	$K(B_1)$	G'_a	G'_b	$K(B_2)$	$P_{ek}(B_1)$	$P_{ek}(B_2)$	M_1	M_2	C_m	P	B_1	B_2	M_{nt}	M_{lt}	M_u
FR-1	Col. 1	1.644	0.000	0.645	4.145	0.000	1.460	5640.29	1100.82	105.49	208.43	0.398	54.72	1.000	1.052	208.43	-409.35	-222.33
	Col. 2	1.644	0.000	0.645	4.145	0.000	1.460	5640.29	1100.82	-105.49	-208.43	0.398	54.72	1.000	1.052	-208.43	-406.79	-636.50
	Col. 3	1.325	1.644	0.820	2.489	4.145	1.880	3489.74	663.90	429.60	558.27	0.292	22.32	1.000	1.035	558.27	-141.34	412.01
	Col. 4	1.325	1.644	0.820	2.489	4.145	1.880	3489.74	663.90	-429.60	-558.27	0.292	22.32	1.000	1.035	-558.27	-141.71	-704.91
FR-2	Col. 1	1.416	0.000	0.640	2.913	0.000	1.360	5283.31	1170.01	111.11	222.05	0.400	60.96	1.000	1.055	222.05	-728.80	-546.81
	Col. 2	1.416	0.000	0.640	2.913	0.000	1.360	5283.31	1170.01	-111.11	-222.05	0.400	60.96	1.000	1.055	-222.05	-726.62	-988.61
	Col. 3	1.157	1.416	0.800	2.379	2.913	1.740	2333.84	493.35	178.93	204.66	0.250	38.64	1.000	1.085	204.66	-368.36	-195.00
	Col. 4	1.157	1.416	0.800	2.379	2.913	1.740	2333.84	493.35	-178.93	-204.66	0.250	38.64	1.000	1.085	-204.66	-368.54	-604.52
	Col. 5	1.128	1.157	0.770	1.815	2.379	1.600	2519.24	583.46	292.28	435.33	0.331	16.32	1.000	1.029	435.33	-156.64	274.18
	Col. 6	1.128	1.157	0.770	1.815	2.379	1.600	2519.24	583.46	-292.28	-435.33	0.331	16.32	1.000	1.029	-435.33	-156.72	-596.56
FR-4	Col. 1	0.847	0.000	0.612	1.724	0.000	1.260	4053.80	956.36	93.52	186.81	0.400	68.56	1.000	1.075	186.81	-423.58	-268.49
	Col. 2	1.034	0.000	0.625	2.104	0.000	1.290	9611.27	2256.12	0.00	0.00	0.600	153.27	1.000	1.075	0.00	-997.63	-1072.33
	Col. 3	0.847	0.000	0.612	1.724	0.000	1.260	4053.80	956.36	-93.52	-186.81	0.400	68.56	1.000	1.075	-186.81	-419.48	-637.70
	Col. 4	0.387	0.847	0.700	0.788	1.724	1.385	1504.24	384.25	155.35	175.28	0.245	43.75	1.000	1.132	175.28	-221.91	-75.99
	Col. 5	0.437	1.034	0.715	0.888	2.104	1.450	3428.97	833.76	0.00	0.00	0.600	99.70	1.000	1.132	0.00	-486.72	-551.11
	Col. 6	0.387	0.847	0.700	0.788	1.724	1.385	1504.24	384.25	-155.35	-175.28	0.245	43.75	1.000	1.132	-175.28	-222.13	-426.80
	Col. 7	0.110	0.387	0.605	0.208	0.788	1.160	803.23	218.49	84.70	91.37	0.229	19.32	1.000	1.110	91.37	-81.63	0.75
	Col. 8	0.107	0.437	0.610	0.202	0.888	1.180	1535.72	410.40	0.00	0.00	0.600	45.37	1.000	1.110	0.00	-157.09	-174.38
	Col. 9	0.110	0.387	0.605	0.208	0.788	1.160	803.23	218.49	-84.70	-91.37	0.229	19.32	1.000	1.110	-91.37	-82.01	-182.40

Analysis with Connection III-16
Nonsway Loads: with modified initial stiffness
Sway Loads: with stiffness by beam-line

The core of a spreadsheet program is the worksheet. A worksheet is built around a structure of rows (usually labeled numerically) and columns (labeled alphabetically). The intersection of a row and a column is called a cell. Each cell has a unique address that describes its column and row position. The cell structure is used to organize or hold data (values), formulas, or labels. Thus, if a worksheet is properly programmed, it can perform a large number of operations and calculations with a few keystrokes.

The effectiveness of the worksheet environment is at its best when the elements of data being manipulated are related and dependent on each other. In the problem at hand, to determine the design moment M_u, one needs to determine M_{nt} and M_{lt} by first-order analysis and evaluate the values of B_1 (which requires P, C_m, and P_{ek}) and B_2 (which requires P and P_{ek}). Both amplification factors (B_1 and B_2) need the effective length factor K, which in turn is a function of G_A and G_B. The end restraint factors (G_A and G_B) are functions of the moment of inertia (I) and the length (L) of all members meeting at the joint under consideration. In the case of flexible frames, connection stiffness values R_{ko} and R_{kb} are also involved, as well as modified expressions for the beam stiffness and the relative restraint factor (G).

Thus, the analysis procedure is actually a chain of operations performed sequentially for each member to determine the necessary values. A change in one variable of this hierarchy affects all subsequent quantities.

5.2 Advantages of Spreadsheet Programming

The selection of the spreadsheet format is inspired by a number of important factors, among them:

1. The worksheet, once properly programmed, is reusable for solving virtually an unlimited number of problems with slight modifications when needed.
2. The ability to copy and move cell contents (values, formulas, or labels) speeds up the programming process significantly for this type of problem. This is because identical formulas are applied to most frame members.
3. Updating a worksheet program to fit different frame configurations is very simple. This is done by inserting rows and/or columns as needed without affecting the worksheet computational setup, since all formulas are updated automatically according to the new positions after each insertion.
4. The spreadsheet format is ideal for frame design and selection of member sections, since this is done in a cyclic manner until the right section is picked.
5. ASCII format files, which is the format of the output of first-order analysis, makes it possible to directly implement this output in the worksheet. This is demonstrated in the upcoming example.

5.3 Organization

The presentation of the analysis procedure in a spreadsheet

Table 6. Frame Properties							
DATA PREPARATION A. Member Properties							
	Member	I	L	R_{ko}	R_{kb}	I'_{ko}	I'_{kb}
FR-1	Col. 1	170	144				
	Col. 2	170	144				
	Col. 3	170	144				
	Col. 4	170	144				
	Beam 5	843	288	163640	123050	413.7493	164.0374
	Beam 6	375	288	163640	129810	256.5846	136.5951
FR-2	Col. 1	184	156				
	Col. 2	184	156				
	Col. 3	127	156				
	Col. 4	127	156				
	Col. 5	127	156				
	Col. 6	127	156				
	Beam 7	843	300	163640	157450	422.3517	205.3409
	Beam 8	843	300	163640	157450	422.3517	205.3409
	Beam 9	291	300	163640	145160	216.5495	134.5529
FR-4	Col. 1	110	144				
	Col. 2	272	144				
	Col. 3	110	144				
	Col. 4	53.4	144				
	Col. 5	127	144				
	Col. 6	53.4	144				
	Col. 7	21.3	144				
	Col. 8	41.4	144				
	Col. 9	21.3	144				
	Beam 10	612	240	163640	154410	321.4601	157.9958
	Beam 11	612	240	163640	154410	321.4601	157.9958
	Beam 12	612	240	163640	154410	321.4601	157.9958
	Beam 13	612	240	163640	154410	321.4601	157.9958
	Beam 14	612	240	163640	171190	321.4601	170.3854
	Beam 15	612	240	163640	171190	321.4601	170.3854

environment can be outlined by the following steps:

1. Conducting the first-order analysis to determine M_{nt} and M_{lt}.
2. The development of the worksheet program.
3. Inputing the frame data and the results of the first-order analysis into the worksheet.
4. Management of member data and forces for final worksheet calculations.

There are a number of commercial spreadsheet and integrated software programs. Among them: Lotus 1-2-3,[9], Excel,[4] Quattro,[10] and others. These programs are much the same in principle and functionality. They differ by some features, but all share the same essential spreadsheet functions and operations. A worksheet program created by one of them can be translated or imported for use by the others. The worksheet program developed here was created with Symphony.[11] The program is organized in such a way that it divides the work area into three distinctive areas (or ranges, in spreadsheet terminology):

1. The top range (FRAME ANALYSIS) is where most operations take place to determine the different variables and, ultimately, the design moment M_u.
2. The middle range (DATA PREPARATION) contains member properties and connection stiffnesses.
3. The bottom range (MEMBER FORCES) contains the imported output of the first-order analysis which is member forces.

For illustration, an example is selected from the comparative study conducted earlier in Sec. 4. Namely, the analysis of different frame configurations with the flexible connection III-16, except that frames FR-3 and FR-5 were excluded for space constraints. This is shown in Tables 5, 6, and 7. These figures are actually fragments of a single worksheet display. They are shown separately here to demonstrate the contents of each of the three areas (ranges) mentioned earlier.

5.4 Management of the Worksheet Data

The output of first-order analyses (both sway and nonsway)

Table 7. Member Forces								
B. Member Forces								
Member No.	**Node i**	**Axial**	**Shear**	**Moment**	**Node j**	**Axial**	**Shear**	**Moment**
FR-1 Nonsway								
1	1	54.72	2.18	105.49	3	54.72	-2.18	208.43
2	2	54.72	-2.18	-105.49	4	-54.72	2.18	-208.43
3	3	22.32	6.8602	429.6	5	-22.32	-6.8602	558.27
4	4	22.32	-6.8602	-429.6	6	-22.32	6.8602	-558.27
FR-1 Sway								
1	1	-2.9262	-4.3359	-409.35	3	2.9262	4.3359	-215.02
2	2	2.9262	-4.3041	-406.79	4	-2.9262	4.3041	-213
3	3	-0.9828	-1.4337	-65.116	5	0.9828	1.4337	-141.34
4	4	0.9828	-1.4463	-66.558	6	-0.9828	1.4463	-141.71
FR-2 Nonsway								
1	1	60.96	2.1356	111.11	3	-60.96	-2.1356	222.05
2	2	60.96	-2.1356	-111.11	4	-60.96	2.1356	-222.05
3	3	38.64	2.4589	204.66	5	-38.64	-2.4589	178.93
4	4	38.64	-2.4589	-204.66	6	-38.64	2.4589	-178.93
5	5	16.32	4.6642	292.28	7	-16.32	-4.6642	435.33
6	6	16.32	-4.6642	-292.28	8	-16.32	4.6642	-435.33
FR-2 Sway								
1	1	-8.3033	-6.9559	-728.69	3	8.3033	6.9559	-356.43
2	2	8.3033	-6.9321	-726.5	4	-8.3033	6.9321	-354.9
3	3	-4.0034	-4.213	-288.94	5	4.0034	4.213	-368.29
4	4	4.0034	-4.219	-289.7	6	-4.0034	4.219	-368.47
5	5	-1.044	-1.4876	-75.508	7	1.044	1.4876	-156.56
6	6	1.044	-1.4884	-75.549	8	-1.044	1.4884	-156.64
FR-4 Nonsway								
1	1	68.564	1.9467	93.519	2	-68.564	-1.9467	186.81
2	5	153.27	-5.6E-16	-5.1E-14	6	-153.27	5.6E-16	-3.1E-14
3	9	68.564	-1.9467	-93.519	10	-68.564	1.9467	-186.81
4	2	43.749	2.2961	155.35	3	-43.749	-2.2961	175.28
5	6	99.703	-3.7E-16	-2.5E-14	7	-99.703	3.7E-16	-2.9E-14
6	10	43.749	-2.2961	-155.35	11	-43.749	2.2961	-175.28
7	3	19.318	1.2227	84.696	4	-19.318	-1.2227	91.366
8	7	45.365	-1.7E-16	-1.1E-14	8	-45.365	1.7E-16	-1.3E-14
9	11	19.318	-1.2227	-84.696	12	-19.318	1.2227	-91.366

is imported into the worksheet. This consists of member forces that fill the lower range of the worksheet. To include these values in the upper range where most calculations take place, one may copy the values one by one to the appropriate locations. Since only a small portion of the worksheet can be viewed at one time, switching between different screens will be needed to manipulate data. To avoid this, the spreadsheet program allows for opening several windows to view different ranges at the same time, thus easing the process of manipulating data for final execution of the worksheet.

```
A1:                                                                  SHEET
    A         B          C          D          E          F          G          H
1
2   Analysis with Connection III-16
3   Nonsway Loads : with modified initial stiffness
4   Sway Loads    : with stiffness by beam-line
5
6                         Ga         Gb        K(B1)       Ga         Gb        K(B2)
7   ==========================================================================
8   FR-1      Col. 1     1.644      0.000      0.645      4.145      0.000      1.460
9             Col. 2     1.644      0.000      0.645      4.145      0.000      1.460
10
11            Col. 3     1.325      1.644      0.820      2.489      4.145      1.880
12            Col. 4     1.325      1.644      0.820      2.489      4.145      1.880
13  --------------------------------------------------------------------------
14  FR-2      Col. 1     1.416      0.000      0.640      2.913      0.000      1.360
15            Col. 2     1.416      0.000      0.640      2.913      0.000      1.360
16
17            Col. 3     1.157      1.416      0.800      2.379      2.913      1.740
18            Col. 4     1.157      1.416      0.800      2.379      2.913      1.740
19
20            Col. 5     1.128      1.157      0.770      1.815      2.379      1.600
                                                                            MAIN
05-Apr-89  03:46 PM                          Zoom
```

Fig. 10. Spreadsheet display.

```
G105:                                                                SHEET
      J          K          L                      F          G          H
6    Pek(B2)     M1         M2             103  Moment    Node j      Axial
7    ===============================       104  ===============================
8    1100.82    105.49     208.43          105
9    1100.82   -105.49    -208.43          106   105.49        3     -54.72
10                                         107  -105.49        4     -54.72
11    663.90    429.60     558.27          108    429.6        5     -22.32
12    663.90   -429.60    -558.27          109   -429.6        6     -22.32
13   -------------------------------       110
14   1170.01    111.11     222.05          111
15   1170.01   -111.11    -222.05          112  -409.35        3     2.9262
16                                         113  -406.79        4    -2.9262
17    493.35    178.93     204.66          114  -65.116        5     0.9828
18    493.35   -178.93    -204.66          115  -66.558        6    -0.9828
19                                         116
20    583.46    292.28     435.33          117
21    583.46   -292.28    -435.33          118   111.11        3     -60.96
22   -------------------------------       119  -111.11        4     -60.96
23    956.36     93.52     186.81          120   204.66        5     -38.64
24   2256.12      0.00       0.00          121  -204.66        6     -38.64
25    956.36    -93.52    -186.81          122   292.28        7     -16.32
                                  MAIN                                  FORCE
05-Apr-89  03:45 PM
```

Fig. 11. Multiple-window display of the spreadsheet.

There are several ways of opening additional windows in a worksheet. The one selected here is done by splitting the screen vertically into two halves. Figure 10 shows the Main window which includes the upper left corner of the worksheet as displayed by Symphony.[11] Figure 11 shows the Main window alongside the "Child" window named Forces which is created by splitting the former vertically. It can be seen how this process eases data manipulation by reducing the amount of data in this window and by aligning cells, the contents of which need to be moved or copied from one window to another. Either one of these windows can be zoomed in or out at any time for viewing a larger set of data.

The determination of the effective length factor can be done either manually by using the AISC LRFD charts,[1] or numerically by switching to a computer program that handles this task outside the spreadsheet environment. Attempts to program the spreadsheet to perform this procedure internally have not, so far, been successful because of the limited functions available for iterational solutions of trigonometric functions involved.

5.5 Summary and Conclusions

The simplified analysis procedure for unbraced flexible frames uses a number of assumptions and models in its formulation. Experimental data and numerical examples are used to evaluate these models and to illustrate the applicability of the analysis procedure as a whole. It has been shown that analytical expressions used for evaluating the initial stiffness and ultimate moment of connection give very good predictions of these values. The performance of the idealized connection models (R_{ko} and R_{kb}) as utilized in the analysis procedure is also demonstrated. It can be concluded that the analysis of flexible frames by B_1 and B_2 concept is feasible if proper modifications are undertaken.

Finally, the implementation of frame analysis on personal computers is demonstrated in a spreadsheet format. Based on our personal experience, the spreadsheet format has been found very efficient for such type of design problems.

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