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Seismic Retrofit of an Existing Multi-Story Wood Frame Structure

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Abstract

This paper discusses the background and methodology associated with the seismic upgrading of a large multi-unit residential project. The advantages of using a rigid diaphragm analysis for the design and retrofit of this type of structure are demonstrated. The development of computer spread sheet analysis tool greatly aided in the design of the retrofit project.

Project Description and Background

The project under study consisted of a 340-unit condominium complex in Southern California. The development consisted of five individual four-story wood frame buildings constructed on top of a large single level pre-stressed post-tensioned concrete parking garage structure. The five buildings were all very similar and involved basically 6 different unit types arranged in a "U" shaped layout with a central corridor serving the units. (See Fig. 1) Exterior walls were stucco finished and contained numerous openings, exterior decks and plan offsets. Two swimming pools, two tennis courts, a handball court and a recreation/exercise facility also were present on the site.

Architectural issues, dealing with roof leaks, window leaks, site drainage, plumbing noises, sound control between units, etc. resulted in the initial complaints and subsequent litigation. Invasive inspections of the wood framed superstructure portion of the project opened up the proverbial "can of worms" of construction defects most of which related to the seismic resistance of the structure. The inspections revealed that most of the lateral load resisting systems were improperly constructed or were missing or significantly compromised. Reanalysis of the project by the consultants hired by the homeowners also revealed that structural design problems were also present in both the superstructure and the garage structure under the complex.

After extensive investigations and many mediation sessions involving the developer, general contractor, numerous subcontractors, architects and engineers the litigation was finally settled and the homeowners were paid a sum of money to address the various problems at the site. After deducting the cost and fees paid to experts, attorneys, inspection contractors and others, the homeowners engaged our firm to establish a program to address the various structural defects found at the site and develop a plan for the seismic retrofit of the structure within a limited budget. As our first activity, we had to review all the claims and sort out the serious from the trivial, and prepare various options on how to best spend the funds available to obtain the most benefit to the structure in the way of improved anticipated seismic performance.

Retrofit Methodology

A retrofit scheme, which consisted of utilizing the long corridor walls and selected interior walls and party walls for enhanced performance was determined to be the best approach. The original design utilized the traditional tributary area method of lateral design and many of the longer walls, due to the lower demand indicated by the design method, were constructed using gypsum wallboard as the shear resisting element. The design code used in the original construction was the 1985 code, which was prior to the 50% reduction requirement for gypsum board walls in seismic zones 3 & 4. Many of the gypsum board walls were also specified to be blocked and nailed with a heavy nail pattern. I don't believe that any of these special gypsum board walls were found to be properly constructed.

By using a rigid diaphragm analysis and heavily nailed ½ inch structural I plywood shear walls with metal straps at the vertical joints along with extensive shear transfer hardware, as much lateral force as practical was drawn into the new retrofitted walls. This retrofit activity thus removed considerable demand from the existing shear walls not scheduled for retrofit although many were found to be defective in one manner or another.

Analysis

Using a spreadsheet for the analysis (See Fig. 2), we were able to model all of the more than 200 shear walls on each floor for each building. The various wall assemblies both existing and retrofitted were modeled both as to stiffness and allowable load code capacity. Each wall type (approximately 15 total) was given a letter designation and a wall table was created (See Fig. 3) that would indicate the stiffness of the material and the allowable load for that assembly. The stiffness of the wall type was based on the deflection formula $vh/Gt + .75\ h\ e_n$ which is the standard formula for plywood shear wall deflection, except that the cord or end post strain is not included. (This strain is a relatively small contributor to deflection especially when viewed in comparison to hold-down distortion) At new shear walls it was assumed the wall and its connections were fully code compliant, while existing plywood shear wall that were not scheduled for retrofit were reduced by 20% for both stiffness and allowable load.

To account for rocking of the shear walls due to movement in the uplift devices a ¼ inch vertical movement was incorporated into the formula for wall element deflection. ($\Delta = h\ \Delta_{hd}/L$ where Δ_{hd} = ¼ inch) Thus for walls with height to length ratios of less than one, this effect on the stiffness was small but for narrow walls with high aspect ratio the effect of rocking was very significant and often resulted in a greater deflection than that due to the shear panel distortion. The spreadsheet automatically computed the distribution of loads to the various walls and included both torsion due to the eccentricity between the center of mass and center of rigidity along with the accidental torsion required by the code. The final column of the spreadsheet listed the Demand / Capacity ratio for the various walls. The beauty of this system was that we could play with the wall selection type and see instantly how it effected the D/C ratio of all the walls. Provided the new walls were less that a D/C ratio of 1.0 and the existing wall were less than about 0.75 (note that for plywood walls we had already reduced the capacity by 20 % for stiffness and allowable load) we were satisfied that we were going to be greatly improving the existing system. For some gypsum board walls that were not scheduled for retrofit or change D/C ratios were indicated to be substantially above a 0.75 ratio. In order to reduce the D/C ratio we had to partially take the wall out of the system by designating them as a discounted wall. This designation in the table in effect reduced their stiffness in half as well as their allowable load by one half. This resulted in an even larger reduction in demand and the resulting D/C ratio in the spreadsheet was reduced below the desired maximum value. This manipulation is similar to what I believe actually happens in the real structure. The wall becomes overloaded tearing at the nails results in a loss of both the stiffness and strength with a redistribution of load to the other shear walls, however the loss of load resisting capacity is not total.

The plywood shear wall stiffness used in the analysis did not include the contribution of the gypsum board or the stucco. The code requirements do not allow such combination of materials for shear resistance, however, for modeling the stiffness of the other elements should be included. Dynamic load test conducted of walls with and without gypsum board show that the stiffness and strength may be additive, at lease in the normal range of deformations. (See Fig 4) Additional research is needed in order to better model the shear walls with various material combinations for proper load distribution over the full range of performance.

As it turned out we were fortunate that we invested the time to develop the spreadsheet program. Relocation was a major cost item and the homeowner's board determined that they could not afford to relocate all or even a significant portion of the occupants. It was decided that occupants would only be relocated if work was being done in a bedroom, bath or kitchen of their unit. Thus if only the living room or dinning room was effected or if only the public hall was effected, no relocation would result. In addition we were encouraged to limit doing work in as many units as possible. It turned out that some of the units had some expensive cabinetwork or expensive wall finishes which would be expensive to remove and replace undamaged. These locations were cataloged and given to us to attempt not include these walls in the retrofit plans. This also exempted the same wall in the units above that location, so this project became a real puzzle to solve. Without the spreadsheet, the changes and fine-tuning of the design would not have been practical.

Construction

The retrofit of the buildings was done on a building by building on a more or less production line basis. The contractor started at the lower floor on one building and proceeding up the building and then continuing on to the next building, etc. The same crews would work together and by the end of the project were able to proceed with almost unbelievable speed. The work would start with the demolition of wall finishes in the hall followed by a framing crew adding blocking, shear clips, sill bolts or lag screws. Holes would be drilled for the hold down devices and added studs at the end areas of walls for compression resistance. Constant vacuuming was carried out by the contractor's crews to limit dust and continuous removal of debris was rigorously enforced. Each evening a complete clean up was carried out and areas inspected to remove or reduce any risk to the occupants. During construction occupants were coming and going with minimum interruption during the process. Occupants were requested not to talk to the workers and vise versa. The homeowner's board had their complains procedures in place and the superintendent or his assistant would handle problems as they occurred.

After each section of the work was completed, an inspection and sign off approval of all items such as shears transfer elements or the hold down devices was made. Then the walls were sheathed with plywood and nailed and inspected for proper nailing. Each and ever wall was logged and signed off by the contractor and either a representative of the architects office or an engineer from our office. The enforcement agency allowed us to do these construction inspections as long as the person doing the inspection was a licensed civil engineer or architect. Since, there was no designation for a special wood inspector the city would not approve a deputy inspector for this work. The city's inspector was on the job at least once every day at the early stages and then less often after they were satisfied that the quality was being maintained. The city's inspector would check the inspection book and do spot inspections of some of the elements. Using this inspection procedure the contractor could continue working and close up walls without having to wait for the City inspector.

For work inside of a unit, the choreography of the work was even more intense. A crew would go into the unit each morning, move the furniture and bag off the work area with plastic. Existing finishes would be removed, the wall inspected to verify that there were no surprises. Next the framers would install the sill and top plate shear transfer clips blocking and lags or bolts, along with the designated tie down devices. These elements would be inspected and signed off in the book. The wall would then be sheathed and nailed, inspected and signed off. The area would then be cleaned and bagging removed and furniture replaced. The next morning the process was repeated with the installation of the wallboard and drywall nailing inspected. The wall would then be taped, the nailheads patched using a fast setting drywall mix. A second coating would later be installed and later the joints and walls sanded. A texture spray to match the existing would be applied along with the wood base and trim installed and again the bagging would be removed after a through cleaning and the furniture replaced.

The next day or sometimes a day or two later the process would again repeat with the bagging and furniture removal for the painting and finishing of the wall. The interior of the unit was thus only effected for three or four days. Miscommunications with occupants, unco-operative occupants sometime stretched out the process, but for the most part the complaints from the occupants were surprisingly small. Some owners couldn't understand why we retrofitted some walls in their unit and not the same wall in another similar unit or no retrofit work in the adjacent unit.

Conclusions

Repairs to the complex were completed in less than 10 months at a cost of approximately one and a half million dollars or approximately $ 4,400 per unit. The work was carried out from building to building with a minimum of disturbance to the occupants. Only 10 occupants were relocated during the construction and the maximum time of relocation was one week.

Attempts were made to realistically model the performance and deformations of the various walls; however, more information is needed to create models of these systems over the full range of deformation so that more accurate distribution of loads will be possible.

Acknowledgments

I wish to recognize the contribution of a very active building committee of the homeowner's association lead by Mr. Tim Murphy. The general contractor Valentine Construction project manager Paul Cragen and my associates Stephanie Welsh and Kamal Shaw for their work on this project. In addition, I would like to thank Seb Ficcadenti and Tom Castle of Ficcadenti and Waggoner, for first pointing out the use of a rigid diaphragm analysis analogy as an appropriate analysis tool for this type of structure.

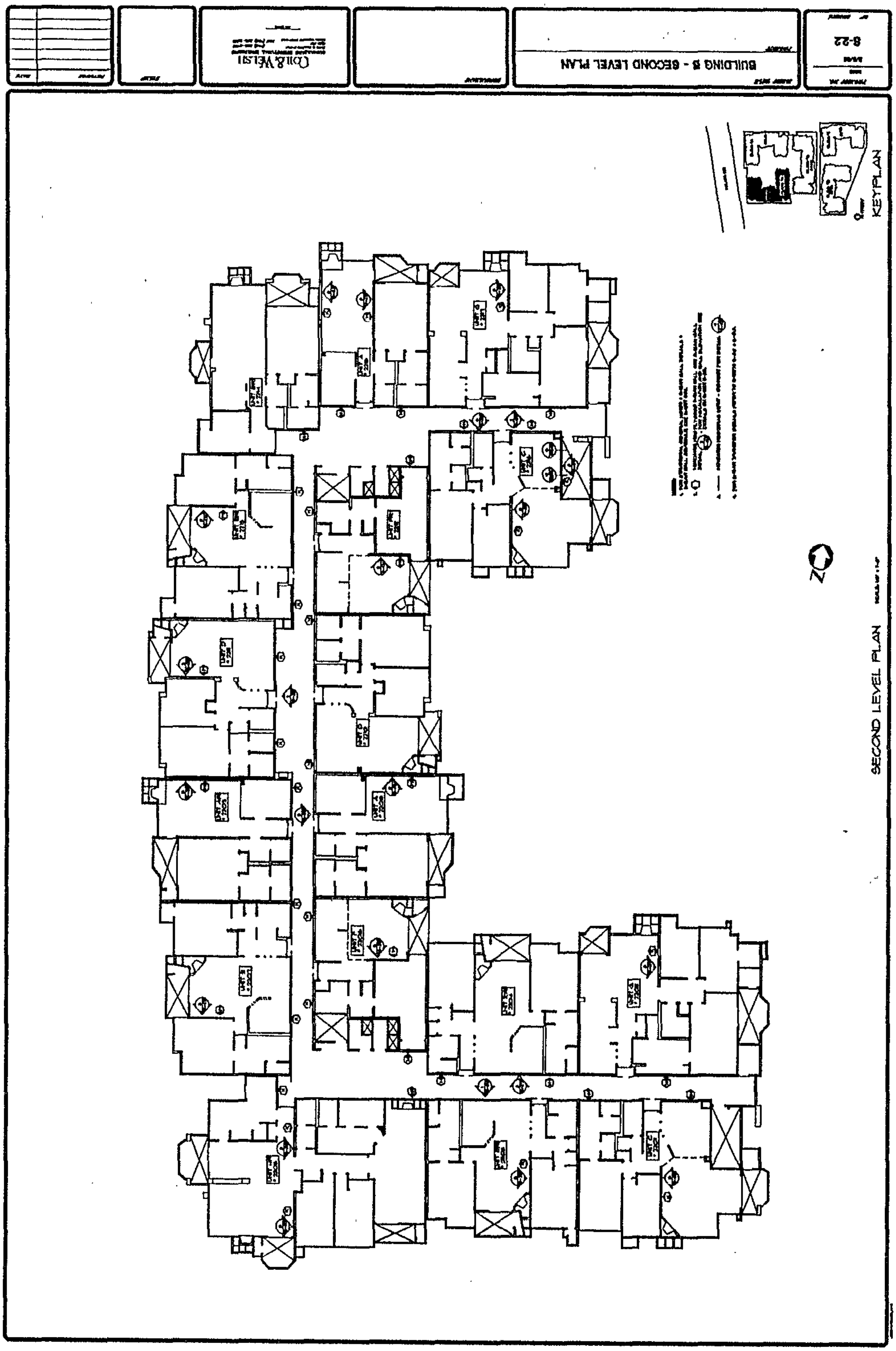

FIGURE 1

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DISTRIBUTION OF SHEAR FORCES

Descr.>>	BUILDING "E"
Level	FIRST LEVEL
Height (ft)	10
Direction	X

Total force (lbs)=	413000
Max "X" Dim (ft)=	231
Max "Y" Dim (ft)=	164
Accidental torsion=	11.55

CENTER OF MASS		
	Xcm (ft)=	97.630
	Ycm (ft)=	108.400

CENTER OF RIGIDITY		
	Xcr (ft) =	96.626
	Ycr (ft) =	110.826

Wall ID	Length "L" (ft)	Height "H" (ft)	"Y" (ft) FROM X AXIS	"X" (ft) From y axis	Material	H/L	S	Sadj.	Rx	Ry	%Fx	%Fy	F(dir) lbs	F(tor) lbs	F(tot) lbs	F/L (lb/ft)	(F/L)all (lb/ft)	DEMAND CAPACITY RATIO
1	11.5	10		1.7	E	0.869565	0.198	0.321	0.000	35.785	0.000	0.007	3018	884	3902	339	440	0.77
2	5	10		4.4	E	2.000	0.198	0.482	0.000	10.375	0.000	0.002	875	249	1124	225	440	0.51
3	6	10		0.1	E	1.666667	0.198	0.435	0.000	13.806	0.000	0.003	1164	347	1511	252	440	0.57
4	6	10		0.1	E	1.666667	0.198	0.435	0.000	13.806	0.000	0.003	1164	347	1511	252	440	0.57
5	7.5	10		8.7	E	1.333333	0.198	0.387	0.000	19.368	0.000	0.004	1633	443	2077	277	440	0.63
6	8.3	10		19.4	A	1.204819	0.967	1.720	0.000	4.826	0.000	0.001	407	97	504	61	100	0.61
7	7	10		16	B	1.428571	0.332	0.720	0.000	9.720	0.000	0.002	820	204	1024	146	230	0.64
8	7.3	10		30.4	B	1.369863	0.332	0.704	0.000	10.366	0.000	0.002	874	179	1053	144	230	0.63
9	5.9	10		24.9	B	1.694915	0.332	0.793	0.000	7.444	0.000	0.002	628	139	767	130	230	0.57
10	5.5	10		25.1	B	1.818182	0.332	0.826	0.000	6.658	0.000	0.001	562	124	685	125	230	0.54
11	4.3	10		27.9	B	2.325581	0.332	0.964	0.000	4.461	0.000	0.001	376	80	456	106	230	0.46
12	4.3	10		27.9	B	2.325581	0.332	0.964	0.000	4.461	0.000	0.001	376	80	456	106	230	0.46
13	5.7	10		33.7	B	1.754386	0.332	0.809	0.000	7.048	0.000	0.001	594	115	710	125	230	0.54
14	10.5	10		34.7	B	0.952381	0.332	0.591	0.000	17.773	0.000	0.004	1499	286	1785	170	230	0.74
15	27.3	10		39	M	0.3663	0.101	0.145	0.000	187.699	0.000	0.038	15830	2815	18646	683	770	0.89
16	18.5	10		39	N	0.540541	0.093	0.159	0.000	116.134	0.000	0.024	9795	1742	11537	624	870	0.72
17	42.1	10		39	M	0.23753	0.101	0.130	0.000	324.684	0.000	0.066	27383	4870	32254	766	770	0.99
18	23	10		39	N	0.434783	0.093	0.146	0.000	157.171	0.000	0.032	13256	2358	15613	679	870	0.78
19	20.5	10		45	B	0.487805	0.332	0.465	0.000	44.128	0.000	0.009	3722	593	4315	210	230	0.92
19A	21.5	10		45	D	0.465116	0.270	0.354	0.000	60.674	0.000	0.012	5117	815	5933	276	344	0.80
20	13	10		46.3	B	0.769231	0.332	0.541	0.000	24.028	0.000	0.005	2027	315	2341	180	230	0.78
21	13.5	10		45.3	N	0.740741	0.093	0.184	0.000	73.436	0.000	0.015	6194	981	7175	531	870	0.61
22	44.9	10		45.3	M	0.222717	0.101	0.128	0.000	351.195	0.000	0.072	29619	4692	34311	764	770	0.99
23	9.33	10		45.3	N	1.071811	0.093	0.224	0.000	41.577	0.000	0.008	3507	555	4062	435	870	0.50

FIGURE 2

Descript.	Material	Shear Modulus "G"	V	#/nail	e_n	t	Delta	F(all)#/ft	D(eff)
DISCOUNTED WALL (GYP EA SIDE ONE LAYER EA SIDE)	A	7500	250	73	0.06	0.5	1.117	100	1.117
5/8" GYP UNBLK-2 SIDE 6d @7:(TOTAL2 LAYERS)	B	15000	250	73	0.03	0.625	0.492	230	0.492
3/8" PLY CDX (EXIST'G) W/8d @ 6"-discounted by 20%	C	90000	250	125	0.047	0.371	0.427	224	0.513
3/8" PLY CDX (EXIST'G) W/ 8d @ 4"- discounted by 20%	D	90000	250	83	0.02	0.371	0.225	344	0.270
3/8" PLY CDX (EXIST'G) W/ 8d @ 3"- discounted by 20%	E	90000	250	62	0.012	0.371	0.165	440	0.198
3/8" PLY CDX (EXIST'G) W/ 8d @ 2"- discounted by 20%	F	90000	250	42	0.011	0.371	0.157	584	0.189
3/8" PLY BLK-1 SIDE 8d @ 6" W/2 LAYERS 5/8" GYP BD	G	90000	250	125	0.024	0.371	0.255	280	0.255
3/8" PLY BLK-1 SIDE 8d @ 4" W/2 LAYERS 5/8" GYP BD	H	90000	250	83	0.012	0.371	0.165	430	0.165
3/8" PLY BLK-1 SIDE 8d @ 3" W/2 LAYERS 5/8" GYP BD	I	90000	250	62	0.008	0.371	0.135	550	0.135
3/8" PLY BLK-1 SIDE 8d @ 2" W/2 LAYERS 5/8" GYP BD	J	90000	250	42	0.007	0.371	0.127	730	0.127
1/2" PLY BLK- 1 SIDE 10d @ 6" W/2 LAYERS 5/8" GYP BD	K	90000	250	125	0.018	0.5	0.191	340	0.191
1/2" PLY BLK- 1 SIDE 10d @ 4" W/2 LAYERS 5/8" GYP BD	L	90000	250	83	0.01	0.5	0.131	510	0.131
1/2" PLY BLK- 1 SIDE 10d @ 3" W/2 LAYERS 5/8" GYP BD	M	90000	250	63	0.006	0.5	0.101	770	0.101
1/2" PLY BLK- 1 SIDE 10d @ 2" W/2 LAYERS 5/8" GYP BD	N	90000	250	42	0.005	0.5	0.093	870	0.093

FIGURE 3

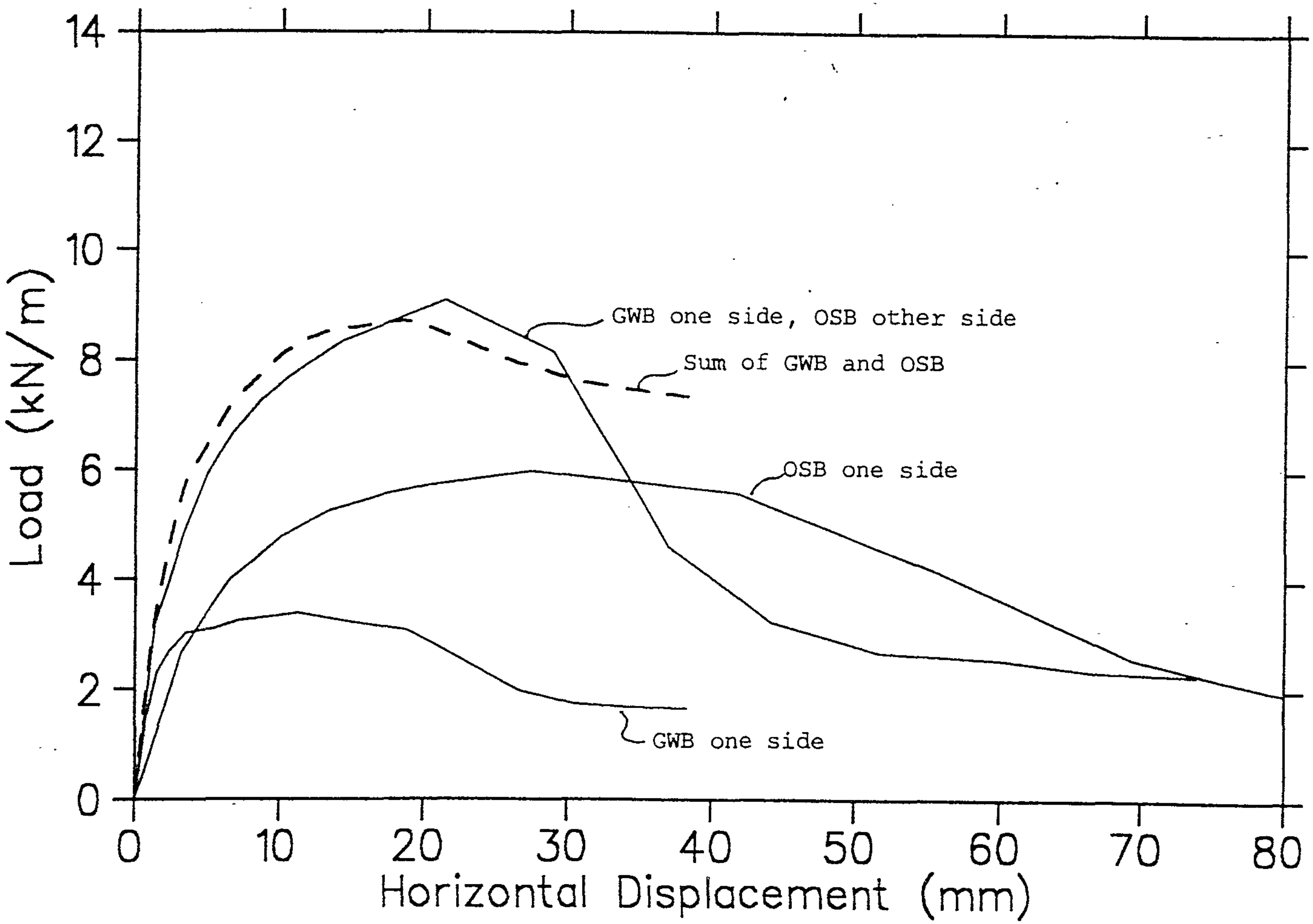

Figure 6 **Contribution of gypsum wall board to the stabilized load carrying capacity when used in combination with OSB**

FIGURE 4