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Effect of platform robustness on inspection planning

Prepared by **EQE International Limited** for the
Health and Safety Executive 2004

RESEARCH REPORT 246

Effect of platform robustness on inspection planning

A Nelson, (Senior Engineer)
D J Sanderson, (Principal Engineer)
S D Thurlbeck, (Principal Engineer)
EQE International Ltd
EQE House
The Beacons
Warrington Road
Birchwood
Cheshire
WA3 6WJ

Offshore platforms require inspection of the underwater portion of the structure on a regular basis. A "robust" structure has inherent redundancies in terms of alternative load paths around any damaged areas and adequately proportioned alternative member strength that allow it to withstand global damage caused by ship impact, fatigue cracking, extreme storms, dropped objects, and other events. Therefore, robust structures may not need as much inspection as other structures, since they are less vulnerable to damage.

Ultimate strength analysis is critical for understanding and defining robustness. Ultimate strength analysis determines the reserve and residual strength, the redundancy and global failure mechanism of the jacket.

EQE has one of the largest in-house data of ultimate strength analyses available, with over 190 pushovers on 65 specific platforms analyzed from around the world. Using this dataset as a basis for investigation, the Health and Safety Executive (HSE) tasked EQE International, Inc. (EQE) to study how platform robustness of platforms can be used for inspection planning. The results of the project are documented in this report.

HSE BOOKS

First published 2004

ISBN 0 7176 2864 7

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EXECUTIVE SUMMARY

INTRODUCTION

Offshore platforms require inspection of the underwater portion of the structure on a regular basis. A “robust” structure has inherent redundancies in terms of alternative load paths around any damaged areas and adequately proportioned alternative member strength that allow it to withstand global damage caused by ship impact, fatigue cracking, extreme storms, dropped objects, and other events. Therefore, robust structures may not need as much inspection as other structures, since they are less vulnerable to damage.

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WORK SCOPE

The EQE work scope consisted of four key parts:

Develop dataset. The EQE pushover analyses are contained in various written reports and digital analyses results. This information was desensitized and condensed to form a dataset of pertinent information in spreadsheet format about each of the platforms. The spreadsheet database is one of the deliverables of the project.

2D frame analyses. Review of the dataset indicated that there was insufficient information on the performance of damaged versus undamaged platforms to make good judgment for inspection planning. Therefore, an additional task was developed that analyzed different types of 2D framing schemes (X, K and diagonal braced) in the damaged and undamaged states. This information was later used in conjunction with the dataset information to develop general inspection guidelines.

Evaluation of dataset. The dataset of pushover analysis was divided into a variety of different logical groups (e.g., 8 vs. 6 vs. 4 leg, X vs. K vs. diagonal bracing, etc.) and evaluated to look for trends and other relevant findings. Some of the trends observed in the 2D analyses were used to determine the evaluation parameters.

Inspection planning. The results of the above work were used to develop some general underwater inspection guidelines for offshore platforms.

RESULTS

The dataset was developed from hardcopy and digital information and put into Excel spreadsheet format for easy data manipulation. This was a considerable effort since much of the data was not in consistent format. Table 1 shows an example hardcopy of the dataset (see page ix).

The 2D frame analyses were conducted on five types of framing schemes as shown in Figure 1. Table 2 shows the resulting Residual Resistance Factor (RRF, computed as the ratio of the damaged capacity to the undamaged capacity). As expected, the X bracing has considerable more robustness than K or diagonal braced platforms. The X braced framing had at most about a 50% reduction in capacity for any damaged member versus about an 80% reduction in capacity for the other bracing schemes. The single diagonal bracing scheme is slightly better that the K bracing schemes in terms of damage tolerance (robustness). .

Damage Case	**Residual Resistance Factor (RRF)**				
	X	**K1**	**K2**	**SD1**	**SD2**
Case 1	0.80	0.18	0.17	0.16	0.17
Case 2	0.83	0.18	0.17	0.35	0.37
Case 3	0.48	0.62	0.70	0.51	0.54
Case 4	0.56	0.58	0.55		
Case 5	0.97	0.58	0.53		
Case 6		0.56	0.55		

$$\text{RRF} \quad \frac{\text{Lateral load at Collapse (damaged)}}{\text{Lateral load at Collapse (undamaged)}}$$

Table 2 Performance (RRF) of damaged frames

The dataset evaluation showed that the key factors play a role in platform robustness. This was determined by investigating the general trends in the data and explicit statistical evaluation. Figure 2 shows a general trend of how the ultimate capacity changes with water depth. Figure 3 shows statistically how X braced platforms perform better than K or diagonal braced (curves on the right hand side of the graph have better the performance than curves on the left had side). Several of the key findings are:

- *Platform vintage*. Newer platforms perform better than older platforms. This is an expected result given the advances in design codes and was confirmed by this study.

- *Number of legs*. The higher the number of legs, the better the platform performance in terms of reserve strength ratio (RSR). While RSR is not an explicit measure of robustness (in terms of damage tolerance), a higher RSR does indicate a potentially lower reduction in capacity given the loss or damage to any one platform member.

- *Framing scheme*. The dataset evaluation showed similar results as the 2D analysis in terms of framing, with the X braced framing in 3D platforms analyses performing better than K or single diagonal bracing.

- *Other issues*. Grouting of the leg-pile annulus (which increases platform capacity, particularly joints) and situations where the design wave impacts the deck (older platforms with low set decks, which decreases capacity) were shown to be other issues where there was a consistent trend in the data.

RECOMMENDATIONS

This project has provided an opportunity to put together the various pushover analyses performed in the past and to study the effect of different parameters on the ultimate strength of the platforms. In addition, the effect of bracing schemes on strength and robustness was studied quantitatively by conducting pushover analyses on two-dimensional frames with different bracing schemes. The following recommendations are made to extend this information and to develop a further understanding on the robustness of the platforms and the development of inspection strategies:

- *Extend the dataset to include additional platforms.* The dataset used in this study consisted of a variety of platform types and configurations from around the world; however, most of the data represents shallow water Gulf of Mexico. This effort would involve gathering of new platform ultimate capacity information, with a focus on North Sea type platforms. The data would come from HSE files or perhaps from operators for in-kind exchange of some portion of the results of the project.

- *Extend the results to more complex framing schemes*. This project focused on generally simple framing schemes – a necessary step in understanding platform robustness. This work would involve a combination of additional 2-D (and perhaps 3D) ultimate strength analysis and additional data gathering and evaluation related to new platforms added to the dataset. The focus would be to understand some of the more complex framing schemes that are typically found in North Sea platforms.

- *Develop a risk-based inspection planning process*. The work developed by this project provides an initial basis for prioritized inspections. However, there are numerous factors that must also be accounted for when developing an inspection plan, for example, the consequence of failure of a platform (e.g., manned vs. unmanned), results of previous inspections and any known damage, as mentioned in the ISO and API inspection guidelines. The information developed in the project described in this document, along with other EQE and/or HSE studies (e.g. Flooded Member Detection JIP), provides a good opportunity to develop a risk-based inspection approach that can be used by the HSE to prioritize efforts associated with inspection planning and review.

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Table 1 Dataset of Pushover Results

PLATFORM INFORMATION							JACKET INFORMATION								PILES INFORMATION							DECK INFORMATION					ASSESSMENT INFORMATION																
Platform ID	Push-Over ID	Software	Year Installed	Location	Orientation wrt True North (TN)	Water Depth	Number of Legs	Number of Bays	Long. Batter	Trans. Batter	Long. Bracing (SD,X,K1,K2)	Trans. Bracing (SD,X,K1,K2)	OverLap (K-Joints) (Yes/No/NA)	Joint Can (Yes/No)	Piles Grouted (Yes/No)	Number of Skirt Piles	Number of Leg Piles	Actual Pile Penetration (ft)	Pile OD (in)	Pile WT (in)	Number of Conductors	Deck Size	Deck Leg Spacing	Number of Deck Elevations	Air Gap (ft)	Lower Deck Elev. (ft)	Wave Height (ft)	Time Period (sec)	Current (knot)	Storm Surge (ft)	Wind Speed (knot)	Deck Weight (kips)	Wave in Deck (Yes/No)	Direction of Wave	API 100-Year Base Shear	RSR	Ultimate Base Shear (kips)	Failure Mechanism	BS at First Member Yield	Member Type (Tension,Compression)	Defl. at First Yield (in)	Defl. at Ultimate Load (in)	Node defl. Measured
4 LEGS																																											
P01	P01-NF-01	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	41.02	13	0.305	4.28	80	3860	No	North	685	4.80	3288						
P01	P01-NF-02	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	43.95	13	1.685	4.28	80	3860	No	North East	1150	2.20	2530						
P01	P01-NF-03	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	52.75	13	2.08	4.28	80	3860	No	East	1743	1.85	3225	Piles Fail in Tension and Compression	2615		21	32	
P01	P01-NF-04	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	58.6	13	1.253	4.28	80	3860	No	South East	1717	1.55	2661	Piles Fail in Tension and Compression	2577		22	115	
P01	P01-NF-05	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	55.67	13	0.2	4.28	80	3860	No	South	1165	2.85	3320	Piles Fail in Tension and Compression	3024		28	56	
P01	P01-NF-06	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	49.8	13	0.2	4.28	80	3860	No	South West	1039	2.30	2389	Piles Fail in Tension and Compression				24	
P01	P01-NF-07	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	41.02	13	0.2	4.28	80	3860	No	West	748	4.11	3074	Piles Fail in Tension and Compression				40	
P01	P01-NF-08	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	41.02	13	0.2	4.28	80	3860	No	North West	731	3.20	2339						
P02	P02-NF-01	SACS	1989	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	East	1287	2.63	3379	Compression Braces Buckled. Tension Braces Yileded.				60	
P02	P02-NF-02	SACS	1989	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	South East	1339	2.04	2725	Piles Fail in Tension and Compression				60	
P02	P02-NF-03	SACS	1989	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	South	947	3.69	3499	Compression Braces Buckled. Tension Braces Yileded. Piles Fail				60	
P02	P02-NF-04	SACS	1989	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	South West	819	3.15	2581	Piles Fail in Tension and Compression				39	
P02	P02-NF-05	SACS	1989	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	West	572	5.62	3217	Compression Braces Buckled. Tension Braces Yileded. Piles Fail.				50	
P03	P03-NF-01	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	41.02	13	0.2	4.28	80	3860	No	North	667	5.10	3402	Piles Fail in Tension and Compression				60	
P03	P03-NF-02	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	43.95	13	0.2	4.28	80	3860	No	North East	816	2.85	2324	Piles Fail in Tension and Compression				60	
P03	P03-NF-03	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	52.74	13	1.612	4.28	80	3860	No	East	1598	2.05	3275	Piles Fail in Tension and Compression				60	
P03	P03-NF-04	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	58.6	13	2.092	4.28	80	3860	No	South East	1999	1.45	2898	Piles Fail in Tension and Compression				60	
P03	P03-NF-05	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	55.67	13	1.345	4.28	80	3860	No	South	1464	2.50	3661	Piles Double-Hinged. Piles Fail in Tension and Compression				60	
P03	P03-NF-06	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	49.81	13	0.2	4.28	80	3860	No	South West	1039	2.18	2264						
P03	P03-NF-07	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	41.02	13	0.2	4.28	80	3860	No	West	746	4.22	3148						
P03	P03-NF-08	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	41.02	13	0.2	4.28	80	3860	No	North West	731	3.45	2521						
P04	P04-NF-01	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	East	820	4.06	3326	Compression Braces Buckled. Tension Braces Yielded. Piles Fail.				60	
P04	P04-NF-02	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	South East	1481	1.81	2688	Piles Fail in Tension and Compression				60	
P04	P04-NF-03	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	South	1747	2.01	3515	Compression Braces Buckled. Tension Braces Yielded. Piles Fail.				60	
P04	P04-NF-04	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	South West	1549	1.64	2543	Piles Fail in Tension and Compression				35	
P04	P04-NF-05	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	West	1039	3.12	3242	Compression Braces Buckled. Tension Braces Yielded. Piles Fail.				60	

NA - Not Applicable
SD - Sub-cellar Deck
CD - Cellar Deck
MD - Main Deck

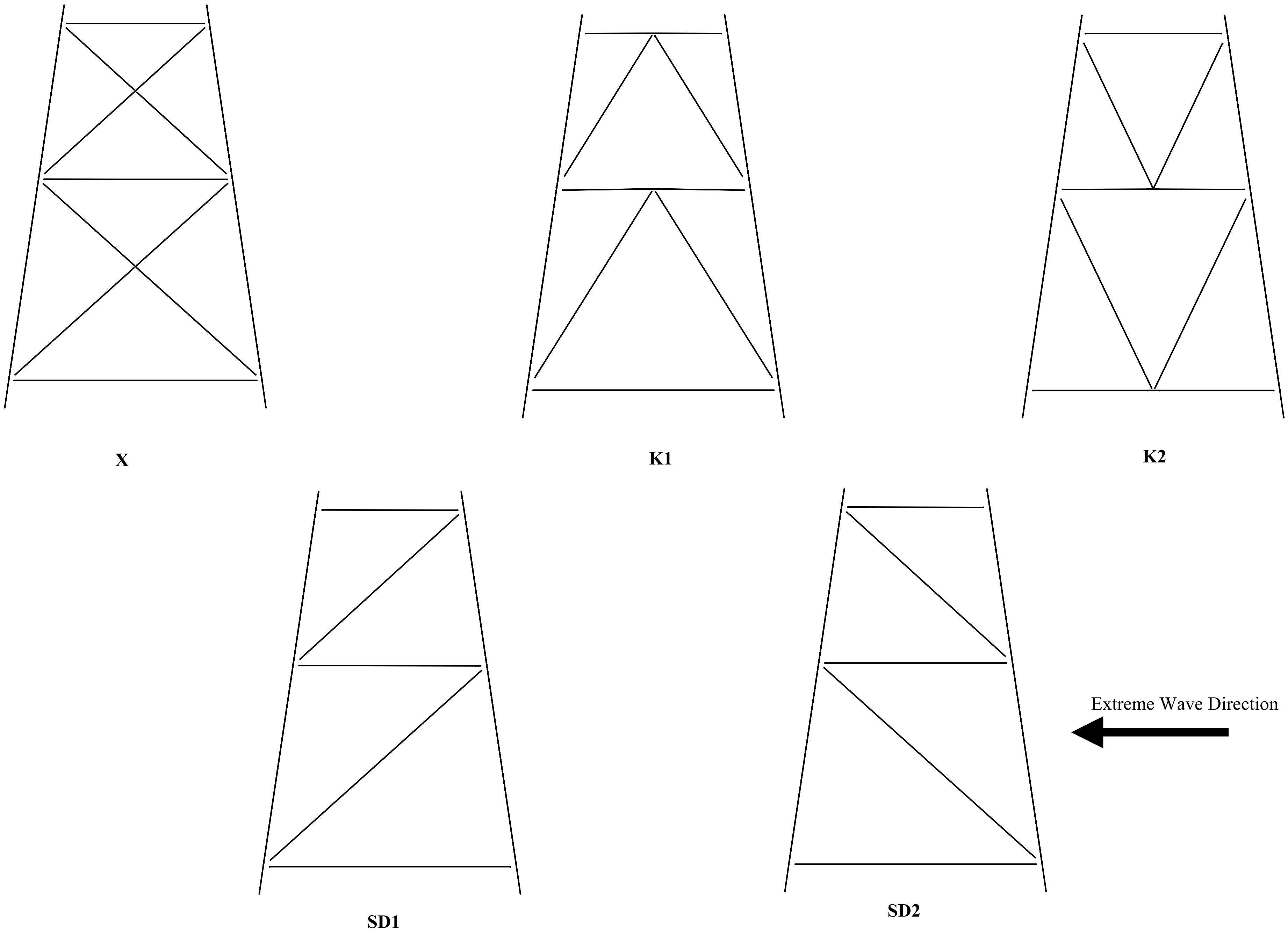

Figure 1 Framing schemes used for two-dimensional analyses

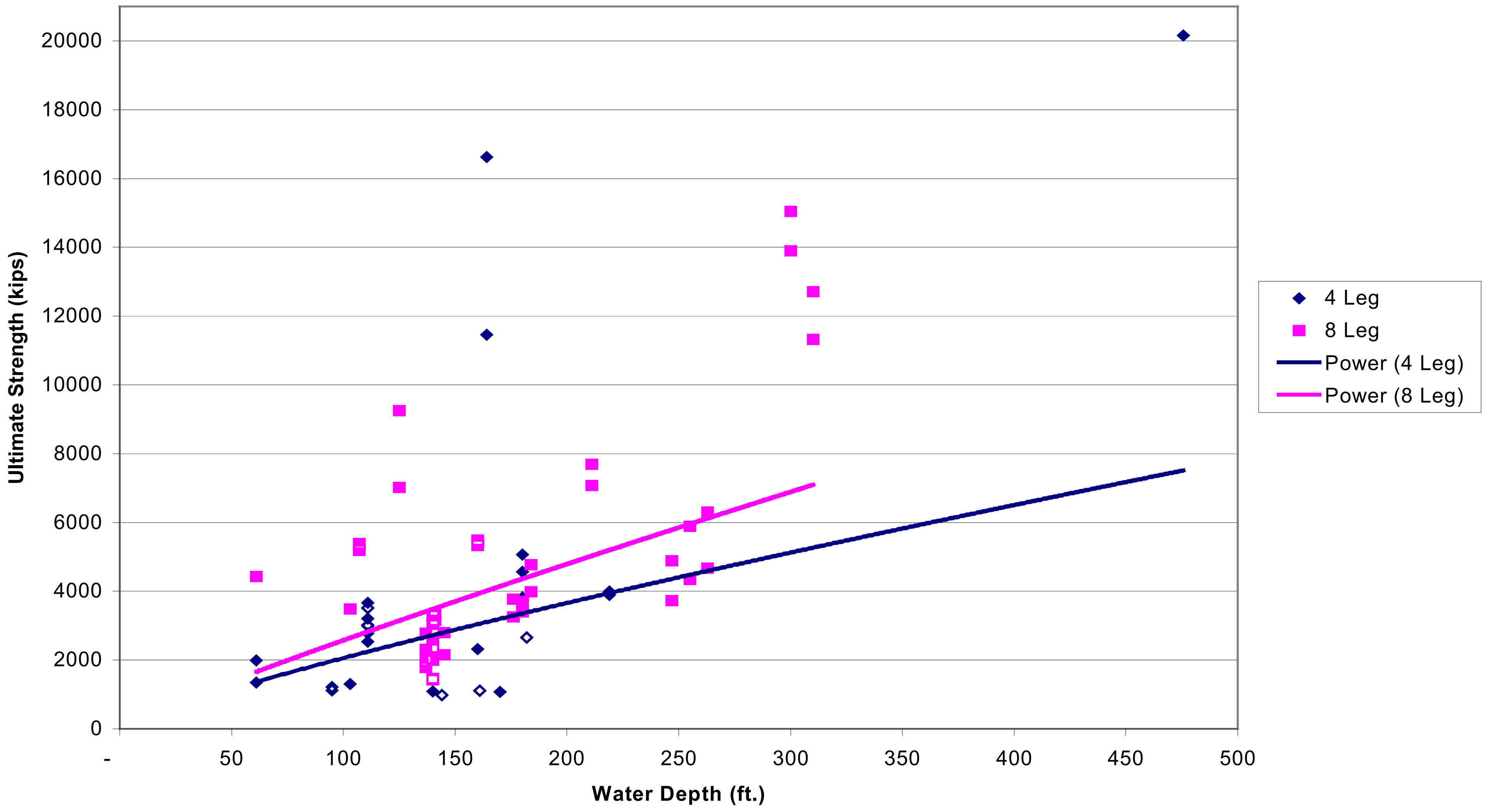

Figure 2 Water depth vs ultimate strength – select platforms

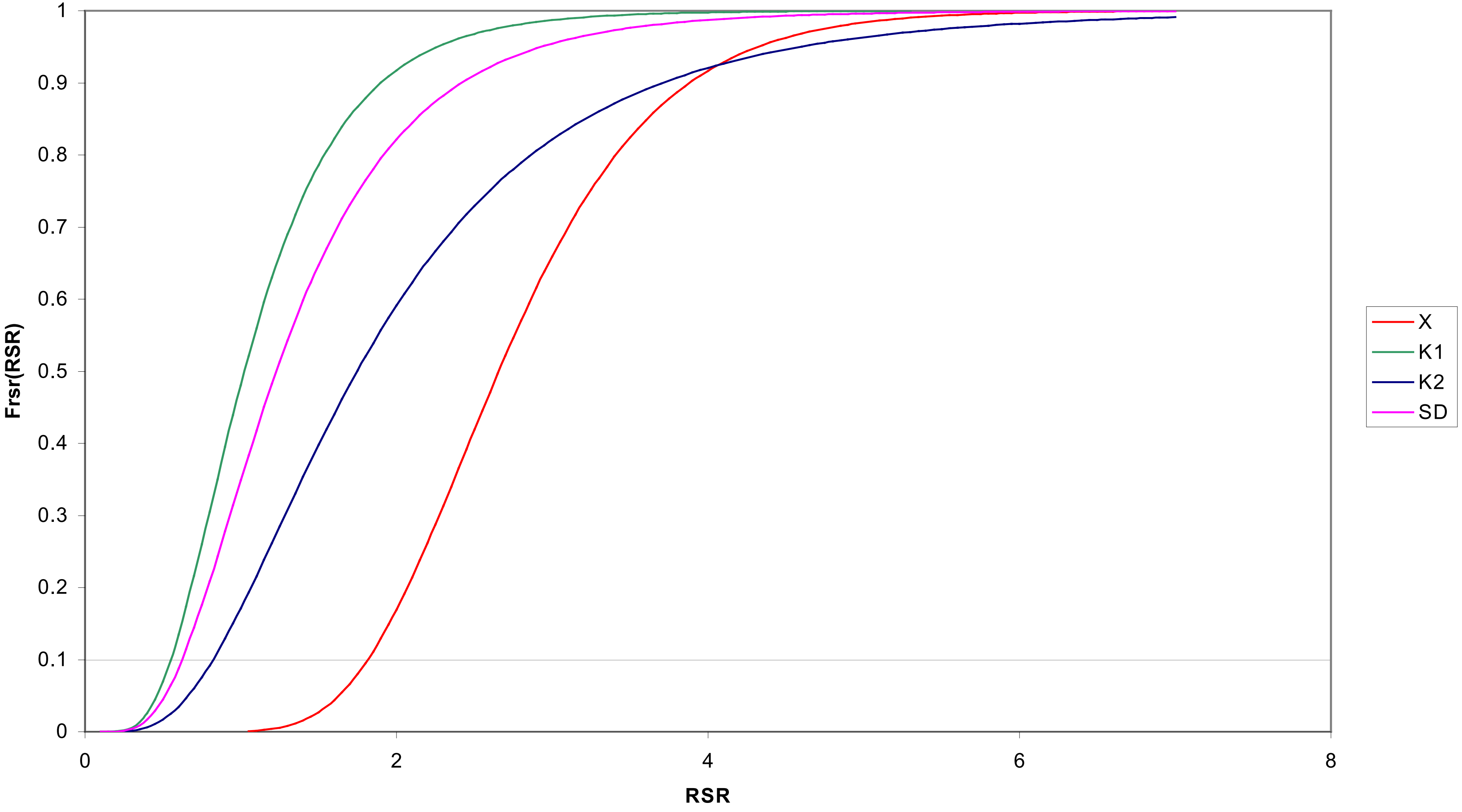

Figure 3 Cumulative distributive functions for different bracing-schemes eight leg-platforms (all vintages)

1.0 INTRODUCTION

1.1 GENERAL REMARKS

Health and Safety Executive tasked EQE International, Inc. to study the effect of robustness of platforms on inspection planning. The ability of offshore platforms to withstand global damage caused by ship impact, fatigue cracking, extreme storms, dropped objects, and other events without collapsing is a function of robustness. A robust structure has inherent redundancies in terms of alternative load paths around damaged areas and adequately proportioned alternative member strength that allow it to survive these types of incidents.

Robustness is a measure of a platform's ability to sustain damage with a limited loss of ultimate capacity and, therefore, reliability [2]. Damage to a robust structure may result in little immediate risk to the facility. For less robust structures, however, a small damage event may significantly diminish the platform's global capacity resulting in a high-risk situation which requires immediate response such as platform de-manning, platform shutdown, or emergency repair. Since damage to robust structures has less affect on the structure's capacity, such platforms may not require the same frequency of inspection as other structures.

Ultimate strength analysis is critical for understanding and defining robustness. Design of offshore structures has traditionally been based on elastic analysis to determine the distribution of forces throughout the structure, for an envelope of design cases. Checks are then performed on a component-by-component basis to ensure that no element of the structure fails to meet the governing criteria. Most offshore jacket structures possess an inherent reserve strength that is greater than the strength of the critical components. Nonlinear frame analyses of offshore platforms provide a better understanding of the overall structural system.

In ultimate strength analysis, the nonlinearities associated with plasticity and large deformations of the components are included explicitly in the finite element modeling of the jacket. The analysis tracks the plastification process within components as well as the interaction between components through redistribution of the forces resulting from changes in local stiffness. Due to plastic behavior prior to failure, the jacket will exhibit reserve strength beyond the required design resistance.

Ultimate strength analysis determines the reserve strength, redundancy, and global mechanism of jacket failure in order to predict the physical behavior of the platform as accurately as possible.

Having analyses of over 65 specific platforms from around the world, EQE has one of the largest in-house datasets of this type of information available. The dataset is a compilation of EQE's work and work by EQE staff while at other organizations. This information was used by EQE in this study to better understand platform robustness.

1.2 SCOPE OF WORK

The following tasks describe the scope of work performed to study platform robustness and its effect on the inspection of platforms:

- *Prepare Dataset*
Develop a single dataset of ultimate strength analyses for a variety of platform configurations, based upon the EQE platform ultimate strength information. For each platform analysis case, identify the type of software used, types of analyses performed, assumptions made, and other pertinent information that may assist in understanding and differentiating results. The data was desensitized to remove information related to the platform owner.

- *Ultimate Strength Analyses of 2-D Frames*
Perform pushover analyses of two-dimensional frames with different bracing schemes in a water depth of 111ft. The frames would be designed to loading that is representative of hydrodynamic loading for a platform in this water depth and would be "pushed-over" in both intact and damaged conditions to study the robustness of the bracing schemes.

- *Identify Trends*
Identify the trends from the dataset that can be used to quantify and, where possible, predict platform performance.

- *Use of Robustness on Inspection Planning*
Develop an understanding of how this information can be used to assist in inspection planning.

1.3 ORGANIZATION OF THE REPORT

Section 2 presents the assumptions in the development of the dataset and details of the data entry fields.

Section 3 discusses the factors affecting the platform performance and the rules developed to compare the performance of the platforms.

Section 4 presents the results of pushover analyses of two-dimensional frames to study the robustness of X-, K- (including K1 (K pointed down) and K2 (K pointed up)), and diagonal-bracing schemes.

Section 5 discusses the statistical analysis of the dataset and how this information relates to platform performance.

Section 6 describes how the results from Sections 4 and 5 could be used to develop an initial understanding of inspection planning for platforms.

Section 7 presents conclusions and recommendations.

2.0 DATASET DEVELOPMENT

2.1 GENERAL REMARKS

Ultimate strength analyses are carried out to determine a jacket's reserve strength, degree of redundancy, and modes of failure. The static pushover consists of a representative profile of lateral wave forces acting on the platform, including those affecting the deck, which is applied in a step-wise increasing manner until the platform collapses [6]. The platform's base shear at the time of failure defines its ultimate capacity. The Reserve Strength Ratio (RSR) may be defined as:

$$\text{RSR} \quad \frac{\text{Lateral load at ultimate strength of the platform}}{\text{Design lateral load}}$$

In this study, the design lateral load is taken as the base shear caused defined by API RP 2A 20th edition [1] environmental recipe.

In other words reserve strength can be defined simply as the ability of a structure to sustain loads in excess of the design load. The fact that a platform has reserve strength does not necessarily indicate over design. Safety factors and conservative design codes build in some reserve strength, which is required to account for wave loading, material and fabrication uncertainties. Additional reserve strength may result from designing for the loads associated with lifting, launch, and installation.

Robustness may be expressed as a function of the relationship between the structure's undamaged and damaged capacities. The capacity of a robust structure would not be greatly affected by common damages. To study the robustness of structures, it is vital to understand the ultimate strength of platforms. As previously noted, EQE has one of the largest in-house datasets of this type of information available that includes the ultimate strength analysis from over 65 platforms. The results have been compiled into a database described further in Section 2.2. The dataset is shown in Table 2.1 (see page 6).

2.2 CONTENTS OF THE DATASET

The ultimate strength of platforms is dependent on several factors. The first step in the development of the dataset was to identify these factors. The following fields are included in the dataset. In the absence of needed data, the associated field was left blank.

2.2.1 Platform information

- ***Platform ID***: Unique value used internally to identify the platform.

- ***Pushover ID***: Push over identifier to identify the pushover analyses on a particular platform. Note that the pushover ID is of the form P01-NF-001 where P01 is the Platform ID, NF represents a nonlinear foundation, and 001 indicates the first pushover analysis on the platform.
- ***Software***: Software used for the analysis. The dataset represents a range of programs including, CAP, SACS, USFOS, SAFJAC, KARMA, ABAQUS, etc.

- ***Year Installed***: Year in which the platform was installed at the current site. EQE performed several pushover analyses as a part of the API CBC study where platforms representative of those found in the Gulf of Mexico were analyzed using various bracing schemes [13, 14]. Where applicable, the year field in these cases shows the API standard to which the platform was designed (i.e. API RP 2A 19th Edition (1989), API RP 2A 20th Edition (1993), etc.).

- ***Location***: Location of the platform. The dataset contains platforms located throughout the world including offshore Gulf of Mexico, California, North Sea, Alaska, and West Africa.

- ***Orientation***: Orientation of the platforms with respect to true north. Where applicable, in the absence of the orientation data, it was assumed that the end-on direction coincided with the principal direction in the Gulf of Mexico.

- ***Water Depth (ft)***: The depth of water in which the platform is located.

2.2.2 Jacket information

- ***Number of Legs***: The number of legs of the platform.

- ***Number of Bays***: The number of bays of vertical bracing typically equal to one less than the number of horizontal plan levels on the jacket. For example, if a jacket located in a water depth of 100 ft. has horizontal plan levels at elevations, (-) 100’, (-) 60’, (-) 25’, and (+) 10’, then, based on this definition, there are 3 bays.

- ***Longitudinal Batter***: Batter of the longitudinal frame of the platform.

- ***Transverse Batter***: Batter of the transverse frame of the platform.

- ***Longitudinal Bracing Scheme***: Bracing scheme of the longitudinal frame of the platform.

- ***Transverse Bracing Scheme***: Bracing scheme of the transverse frame of the platform.

- ***Overlap of K-joints***: Indicates an overlap of braces at K-joint, wherever applicable. Overlapped K-joints have greater capacities than gapped joints.

- ***Joint Can***: This field indicates the presence of joint cans. Platforms with joint cans perform better than those without joint cans.

2.2.3 Pile information

- ***Pile Grout***: Indicates whether or not the leg/pile annulus is grouted. In the absence of the data, the leg/pile annulus was assumed to be not grouted.

- ***Number of Skirt Piles***: Number of skirt piles present.

- ***Number of Leg Piles***: Number of legs containing piles.
- ***Actual Pile Penetration (ft)***: Vertical penetration of the piles below the mudline as installed.

- ***Pile OD (in)***: Outside diameter of the piles at the mudline.

- ***Pile Wall-thickness (in)***: Wall thickness of the piles at the mudline.

- ***Number of Conductors***: Number of conductors carried by the platform. This information is most relevant when we know the number of conductors for which the platform was designed and the number of conductors actually present.

2.2.4 Deck information

- ***Deck Size (Length of the deck (ft) x width of the deck (ft))***: Sizes of the decks. Input the dimensions of all the decks present.

- ***Deck Leg Spacing (ft)***: Spacing of legs at the deck level.

- ***Number of Deck Elevations***: Number of decks present on the platform.

- ***Lower Deck Elevation (ft)***: Elevation of the lowest deck above mean water level.

- ***Air gap (ft)***: Difference between deck height and the calculated crest of the wave. In this study, API 100-year design wave is used to determine the air-gap for the platforms. It was assumed that the wave crest is approximately 60% of the wave height.

2.2.5 Assessment information

- ***Wave Height (ft)***: Wave height at which the platform was pushed over.

- ***Time Period (sec)***: Wave period corresponding to the above wave.

- ***Current (knot)***: Speed of current at which the platform was pushed over.

- ***Storm Surge (ft)***: Height of storm surge used in the analyses.

- ***Wind Speed (knots)***: Wind velocity used in the pushover analysis.

- ***Deck Weight (kips)***: Structural and equipment weights applied to the deck.

- ***Wave in Deck***: Indicates whether or not the API 20th Edition 100-year wave inundates the deck. This field depends on the air-gap described in the previous section. An air-gap greater than 0 indicates no wave-in-deck.

- ***Direction of Wave***: Direction of wave propagation used in the pushover analysis. Typical pushover directions used in the datasets are demonstrated in the Figure 2-1.

- ***API 100-year Base Shear (kips)***: Base shear computed for the API 20th Edition 100-year environmental loading.
- ***Reserve Strength Ratio (RSR)***: Ratio of base shear at ultimate capacity of the structure to the 100-year base shear.

- ***Ultimate Strength (kips)***: Ultimate capacity of the platform for the environmental loading described above.

- ***Failure Mechanism***: Mechanism of platform failure when pushed over.

- ***Base shear at first member yield (kips)***: base shear at the first occurrence of yield.

- ***Member Type***: Type of member (i.e. tension or compression) in which the first yield occurred.

- ***Deflection at First Yield (in)***: Maximum deflection when the first yield occurred.

- ***Deflection at Ultimate Capacity (in)***: Maximum deflection at ultimate capacity (i.e. just prior to collapse).

- ***Node at which Deflections Measured***: Node at which the deflections were measured.

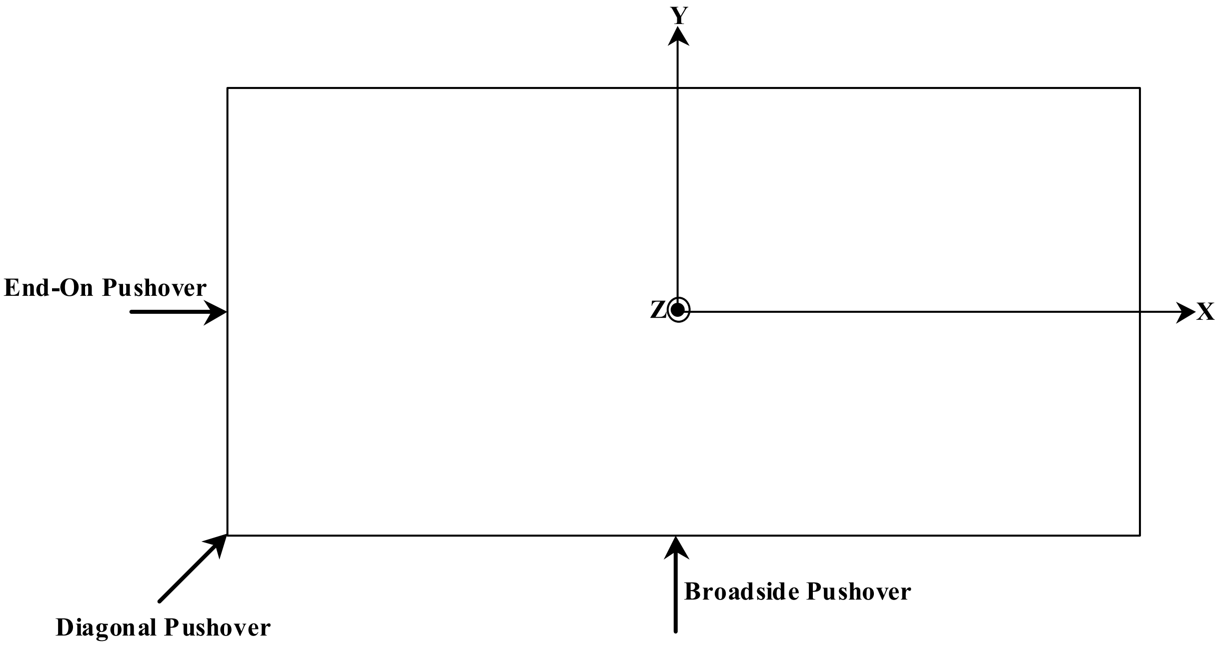

Figure 2-1 Pushover analysis directions

Table 2.1 Dataset of pushover results

PLATFORM INFORMATION							JACKET INFORMATION								PILES INFORMATION							DECK INFORMATION					ASSESSMENT INFORMATION																	
Platform ID	Push-Over ID	Software	Year Installed	Location	Orientation wrt True North (TN)	Water Depth	Number of Legs	Number of Bays	Long. Batter	Trans. Batter	Long. Bracing (SD,X,K1,K2)	Trans. Bracing (SD,X,K1,K2)	OverLap (K-Joints) (Yes/No/NA)	Joint Can (Yes/No)	Piles Grouted (Yes/No)	Number of Skirt Piles	Number of Leg Piles	Actual Pile Penetration (ft)	Pile OD (in)	Pile WT (in)	Number of Conductors	Deck Size	Deck Leg Spacing	Number of Deck Elevations	Air Gap (ft)	Lower Deck Elev. (ft)	Wave Height (ft)	Time Period (sec)	Current (knot)	Storm Surge (ft)	Wind Speed (knot)	Deck Weight (kips)	Wave in Deck (Yes/No)	Direction of Wave	API 100-Year Base Shear	RSR	Ultimate Base Shear (kips)	Failure Mechanism	BS at First Member Yield	Member Type (Tension,Compression)	Defl. at First Yield (in)	Defl. at Ultimate Load (in)	Node defl. Measured
4 LEGS																																												
P01	P01-NF-01	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	41.02	13	0.305	4.28	80	3860	No	North	685	4.80	3288						
P01	P01-NF-02	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	43.95	13	1.685	4.28	80	3860	No	North East	1150	2.20	2530						
P01	P01-NF-03	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	52.75	13	2.08	4.28	80	3860	No	East	1743	1.85	3225	Piles Fail in Tension and Compression	2615		21	32	
P01	P01-NF-04	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	58.6	13	1.253	4.28	80	3860	No	South East	1717	1.55	2661	Piles Fail in Tension and Compression	2577		22	115	
P01	P01-NF-05	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	55.67	13	0.2	4.28	80	3860	No	South	1165	2.85	3320	Piles Fail in Tension and Compression	3024		28	56	
P01	P01-NF-06	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	49.8	13	0.2	4.28	80	3860	No	South West	1039	2.30	2389	Piles Fail in Tension and Compression				24	
P01	P01-NF-07	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	41.02	13	0.2	4.28	80	3860	No	West	748	4.11	3074	Piles Fail in Tension and Compression				40	
P01	P01-NF-08	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-210	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	41.02	13	0.2	4.28	80	3860	No	North West	731	3.20	2339						
P02	P02-NF-01	SACS	1989	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	East	1287	2.63	3379	Compression Braces Buckled. Tension Braces Yileded.				60	
P02	P02-NF-02	SACS	1989	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	South East	1339	2.04	2725	Piles Fail in Tension and Compression				60	
P02	P02-NF-03	SACS	1989	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	South	947	3.69	3499	Compression Braces Buckled. Tension Braces Yileded. Piles Fail				60	
P02	P02-NF-04	SACS	1989	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	South West	819	3.15	2581	Piles Fail in Tension and Compression				39	
P02	P02-NF-05	SACS	1989	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	West	572	5.62	3217	Compression Braces Buckled. Tension Braces Yileded. Piles Fail.				50	
P03	P03-NF-01	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	41.02	13	0.2	4.28	80	3860	No	North	667	5.10	3402	Piles Fail in Tension and Compression				60	
P03	P03-NF-02	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	43.95	13	0.2	4.28	80	3860	No	North East	816	2.85	2324	Piles Fail in Tension and Compression				60	
P03	P03-NF-03	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	52.74	13	1.612	4.28	80	3860	No	East	1598	2.05	3275	Piles Fail in Tension and Compression				60	
P03	P03-NF-04	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	58.6	13	2.092	4.28	80	3860	No	South East	1999	1.45	2898	Piles Fail in Tension and Compression				60	
P03	P03-NF-05	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	55.67	13	1.345	4.28	80	3860	No	South	1464	2.50	3661	Piles Double-Hinged. Piles Fail in Tension and Compression				60	
P03	P03-NF-06	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	49.81	13	0.2	4.28	80	3860	No	South West	1039	2.18	2264						
P03	P03-NF-07	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	41.02	13	0.2	4.28	80	3860	No	West	746	4.22	3148						
P03	P03-NF-08	SACS	1993	Gulf of Mexico	N30W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	190-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	41.02	13	0.2	4.28	80	3860	No	North West	731	3.45	2521						
P04	P04-NF-01	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	East	820	4.06	3326	Compression Braces Buckled. Tension Braces Yielded. Piles Fail.				60	
P04	P04-NF-02	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	South East	1481	1.81	2688	Piles Fail in Tension and Compression				60	
P04	P04-NF-03	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	South	1747	2.01	3515	Compression Braces Buckled. Tension Braces Yielded. Piles Fail.				60	
P04	P04-NF-04	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	South West	1549	1.64	2543	Piles Fail in Tension and Compression				35	
P04	P04-NF-05	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	61.41	13	0	5.76	102	3860	No	West	1039	3.12	3242	Compression Braces Buckled. Tension Braces Yielded. Piles Fail.				60	
P05-A	P05A-NF-01	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	43.95	13	0.2	4.28	80	3860	No	East	834	3.50	2919	Jacket Failure	2711		25	67	
P05-A	P05A-NF-02	SACS	1989	Gulf of Mexico	N70W		4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	52.74	13	1.612	4.28	80	3860	No	SouthEast	1506	2.10	3162.6	Foundation Failure	2711		25	88	
P05-A	P05A-NF-03	SACS	1989	Gulf of Mexico	N70W		4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	58.6	13	2.097	4.28	80	3860	No	South	1780	1.70	3026	Jacket Failure	2670		21	57	
P05-A	P05A-NF-04	SACS	1989	Gulf of Mexico	N70W		4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	55.67	13	1.345	4.28	80	3860	No	South West	1575	1.80	2835	Foundation Failure				47	
P05-A	P05A-NF-05	SACS	1989	Gulf of Mexico	N70W		4	2	1 in 8	1 in 8	X	X	NA	Yes	No	0	4	210-230	42 (ML)	1.625 (ML)	6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	49.81	13	0.2	4.28	80	3860	No	West	1056	2.85	3009.6	Jacket Failure	2746		22	55	
P05-B	P05B-NF-01	SACS	1993	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	SD1,SD2	SD1,SD2	NA	Yes	No	0	4	190-210	42		6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	52.74	13	1.612	4.28	80	3860	No	SouthEast	1428	1.85	2642	Foundation Failure				117	
P05-B	P05B-NF-02	SACS	1993	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	SD1,SD2	SD1,SD2	NA	Yes	No	0	4	190-210	42		6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	58.6	13	2.092	4.28	80	3860	No	South	1686	1.90	3203	Foundation Failure	2529		20	58	
P05-B	P05B-NF-03	SACS	1993	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	SD1,SD2	SD1,SD2	NA	Yes	No	0	4	190-210	42		6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	55.67	13	1.345	4.28	80	3860	No	South West	1495	1.65	2467	Foundation Failure				72	

Table 2.1 Dataset of pushover results

PLATFORM INFORMATION							JACKET INFORMATION								PILES INFORMATION							DECK INFORMATION					ASSESSMENT INFORMATION																
Platform ID	Push-Over ID	Software	Year Installed	Location	Orientation wrt True North (TN)	Water Depth	Number of Legs	Number of Bays	Long. Batter	Trans. Batter	Long. Bracing (SD,X,K1,K2)	Trans. Bracing (SD,X,K1,K2)	OverLap (K-Joints) (Yes/No/NA)	Joint Can (Yes/No)	Piles Grouted (Yes/No)	Number of Skirt Piles	Number of Leg Piles	Actual Pile Penetration (ft)	Pile OD (in)	Pile WT (in)	Number of Conductors	Deck Size	Deck Leg Spacing	Number of Deck Elevations	Air Gap (ft)	Lower Deck Elev. (ft)	Wave Height (ft)	Time Period (sec)	Current (knot)	Storm Surge (ft)	Wind Speed (knot)	Deck Weight (kips)	Wave in Deck (Yes/No)	Direction of Wave	API 100-Year Base Shear	RSR	Ultimate Base Shear (kips)	Failure Mechanism	BS at First Member Yield	Member Type (Tension,Compression)	Defl. at First Yield (in)	Defl. at Ultimate Load (in)	Node defl. Measured
P05-C	P05C-NF-01	SACS	1993	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	SD1,SD2	SD1,SD2	NA	Yes	No	0	4	185-210	42		6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	43.9	13	1.68	4.2	80	3860	No	East	1011	2.50	2528	Jacket Failure	2376		25	58	
P05-C	P05C-NF-02	SACS	1993	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	SD1,SD2	SD1,SD2	NA	Yes	No	0	4	185-210	42		6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	52.7	13	2.08	4.2	80	3860	No	SouthEast	1531	1.75	2679	Foundation Failure				65	
P05-C	P05C-NF-03	SACS	1993	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	SD1,SD2	SD1,SD2	NA	Yes	No	0	4	185-210	42		6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	58.5	13	2.08	4.2	80	3860	No	South	1435	2.10	3014	Jacket & Foundation Failure	2727		26	61	
P05-D	P05D-NF-01	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	SD1,SD2	SD1,SD2	NA	Yes	No	0	4	210-230	42		6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	52.74	13	1.612	4.28	80	3860	No	SouthEast	1426	1.95	2781	Plasticity and Hinging in Jacket & Foundation Failure	2709		30	64	
P05-D	P05D-NF-02	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	SD1,SD2	SD1,SD2	NA	Yes	No	0	4	210-230	42		6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	58.6	13	2.092	4.28	80	3860	No	South	1689	1.75	2956	Jacket	2365		22	62	
P05-D	P05D-NF-03	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	SD1,SD2	SD1,SD2	NA	Yes	No	0	4	210-230	42		6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	55.67	13	1.345	4.28	80	3860	No	South West	1492	1.75	2611	Plasticity and Hinging in Jacket & Foundation Failure	2462		26	87	
P05-E	P05E-NF-01	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	SD1,SD2	SD1,SD2	NA	Yes	No	0	4	210-230	42		6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	43.9	13	1.68	4.2	80	3860	No	East	1110	2.50	2775	Jacket Failure	2664		24	56	
P05-E	P05E-NF-02	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	SD1,SD2	SD1,SD2	NA	Yes	No	0	4	210-230	42		6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	52.7	13	2.08	4.2	80	3860	No	South East	1557	1.75	2725	Foundation Failure				31	
P05-E	P05E-NF-03	SACS	1989	Gulf of Mexico	N70W	111	4	2	1 in 8	1 in 8	SD1,SD2	SD1,SD2	NA	Yes	No	0	4	210-230	42		6	83.25'x73.25' (CD) 83'x84' (MD)	40' (Long) 30' (Tran)	2	26.4	61.5	58.5	13	1.25	4.2	80	3860	No	South	1460	2.05	2993	Jacket & Foundation Failure	2409		24	58	
P06	P06-NF-01	CAP	1968	Alaska	N50W	100	4	1	0	0	X	X	NA		Yes	0	4																										
P07	P07-NF-01	USFOS	1969^{A}	Gulf of Mexico		103	4	3	1 in 7.5	1 in 7.5	K1,K2	K1,K2			Yes	0	4	230	36		10			2	17.2	52	49.88	12.5	1.8	3.5	70		No	90 wrt PlatN.	2390	1.09	2614	Jacket face Diagonal	2212			23	
P07	P07-NF-02	USFOS	1969^{A}	Gulf of Mexico		103	4	3	1 in 7.5	1 in 7.5	K1,K2	K1,K2			Yes	0	4	230	36		10			2	17.2	52	49.88	12.5	1.8	3.5	70		No	90 wrt PlatN.	2390	0.55	1307	Jacket K-brace Joints				8.5	
P08	P08-NF-01		1970	Gulf of Mexico	N30W	160	4	2	1 in 7	1 in 7	X	X	NA	Yes	No	0	4	190-227	36		8	45x45 (CD) 74x74 (MD)		2	9.5	47	67.5	13.5	2.3		85	1241	No	Diagonal	2160	1.18	2556	Pile and Jacket Collapse				>60	At Deck Level +65'
P08	P08-NF-02		1970	Gulf of Mexico	N30W	160	4	2	1 in 7	1 in 7	X	X	NA	Yes	No	0	4	190-227	36		8	45x45 (CD) 74x74 (MD)		2	9.5	47	64.125	13.5	2.3		85	1241	No	Broadside	1966	1.18	2321	Jacket Collapse				84.12	At Deck Level +65'
P09	P09-NF-01		1971	Gulf of Mexico	N10E	182	4	6			K1,K2	K1,K2		No	No	0	4	255	42	1"-2"	10			2	7.6	46	54.6	12.5	1.8	3	70		No	EndOn	1602	1.66	2660	Strut Buckling	2660	Compression		62	
P09	P09-NF-02		1971	Gulf of Mexico	N10E	182	4	6			K1,K2	K1,K2		No	No	0	4	255	42	1"-2"	10			2	7.6	46	57.5	12.5	1.8	3	70		No	Diagonal	2303	1.52	3500	Yielding in Piles and strut buckling	2750			98	
P09	P09-NF-03		1971	Gulf of Mexico	N10E	182	4	6			K1,K2	K1,K2		No	No	0	4	255	42	1"-2"	10			2	7.6	46	51.8	12.5	1.8	3	70		No	Broadside	2598	1.02	2650	Strut Buckling	2650	Compression		86	
P13	P13-NF-01	SACS	1984	Gulf of Mexico	N25W	219	4	4	1 in 10	1 in 10	SD	SD	NA	Yes	Yes	0	4	295	48	2.25	6			2	21.86	61.46	85		3	6.74	106		No	EndOn	1163	3.35	3897	Piles Plunge				36	
P13	P13-NF-02	SACS	1984	Gulf of Mexico	N25W	219	4	4	1 in 10	1 in 10	SD	SD	NA	Yes	Yes	0	4	295	48	2.25	6			2	21.86	61.46	80		2.8	5.92	100		No	Diagonal			3287	Piles Plunge				34	
P13	P13-NF-03	SACS	1984	Gulf of Mexico	N25W	219	4	4	1 in 10	1 in 10	SD	SD	NA	Yes	Yes	0	4	295	48	2.25	6			2	21.86	61.46	85		3	6.74	106		No	Broadside	1963	2.02	3967	Piles Plunge	3724	Compression	25	35	
P16	P16-NF-01		1991	Gulf of Mexico	N15E	468	4	5			X	X			No	4	4								12.1	53.5							No	Broadside			13718	Pile Pull Out					
P16	P16-NF-02		1991	Gulf of Mexico	N15E	468	4	5			X	X			No	4	4								12.1	53.5							No	Diagonal			11566	Pile Pull Out					
P17	P17-NF-01	CAP	1981	West Africa		161	4	4	0	0	SD	SD			No	0	4	109			9					32						3360		EndOn	493	2.25	1107	Vertical Diagonal					
P17	P17-NF-02	CAP	1981	West Africa		161	4	4	0	0	SD	SD			No	0	4	109			9					32						3360		Diagonal	515	2.17	1116	Vertical Diagonal					
P17	P17-NF-03	CAP	1981	West Africa		161	4	4	0	0	SD	SD			No	0	4	109			9					32						3360		Broadside	405	2.77	1120	Vertical Diagonal					
P22	P22-NF-01		1978^{D}	Gulf of Mexico	N41W	95	4	3	1 in 8	1in 8	X,K2	X,K2		Yes (Legs)	No	0	4	180	30	1.75	4	40x40 (CD) 72x72 (MD)		2	<21.15	54.75 (TOS)	48.5	12.5	1.8	3.21	70		No	4 (wrt PN-Clockwise	1125	1.41	1584	Jacket					
P22	P22-NF-02		1978	Gulf of Mexico	N41W	95	4	3	1 in 8	1in 8	X,K2	X,K2		Yes (Legs)	No	0	4	180	30	1.75	4	40x40 (CD) 72x72 (MD)		2	<21.15	54.75 (TOS)	43.4	12.5	1.8	3.21	70		No	49	771	1.42	1096	Jacket					
P22	P22-NF-03		1978	Gulf of Mexico	N41W	95	4	3	1 in 8	1 in 8	X,K2	X,K2		Yes (Legs)	No	0	4	180	30	1.75	4	40x40 (CD) 72x72 (MD)		2	<21.15	54.75 (TOS)	35.8	12.5	1.8	3.21	70		No	94	693	1.80	1250	Jacket					
P22	P22-NF-04		1978	Gulf of Mexico	N41W	95	4	3	1 in 8	1 in 8	X,K2	X,K2		Yes (Legs)	No	0	4	180	30	1.75	4	40x40 (CD) 72x72 (MD)		2	<21.15	54.75 (TOS)	35.8	12.5	1.8	3.21	70		No	139	731	1.62	1184	Pile					
P22	P22-NF-05		1978	Gulf of Mexico	N41W	95	4	3	1 in 8	1 in 8	X,K2	X,K2		Yes (Legs)	No	0	4	180	30	1.75	4	40x40 (CD) 72x72 (MD)		2	<21.15	54.75 (TOS)	35.8	12.5	1.8	3.21	70		No	184	885	1.26	1116	Jacket					
P22	P22-NF-06		1978	Gulf of Mexico	N41W	95	4	3	1 in 8	1in 8	X,K2	X,K2		Yes (Legs)	No	0	4	180	30	1.75	4	40x40 (CD) 72x72 (MD)		2	<21.15	54.75 (TOS)	38.3	12.5	1.8	3.21	70		No	229	1521	0.65	991	Jacket					
P22	P22-NF-07		1978	Gulf of Mexico	N41W	95	4	3	1 in 8	1 in 8	X,K2	X,K2		Yes (Legs)	No	0	4	180	30	1.75	4	40x40 (CD) 72x72 (MD)		2	<21.15	54.75 (TOS)	46	12.5	1.8	3.21	70		No	290	1802	0.67	1216	Pile					
P22	P22-NF-07		1978	Gulf of Mexico	N41W	95	4	3	1 in 8	1 in 8	X,K2	X,K2		Yes (Legs)	No	0	4	180	30	1.75	4	40x40 (CD) 72x72 (MD)		2	<21.15	54.75 (TOS)	51.1	12.5	1.8	3.21	70		No	319	1916	0.69	1324	Pile					
P25	P25-NF-01	CAP	1969	Gulf of Mexico	N12W	61	4	4	1 in 8	1 in 8	K1	K1	No	Yes (Legs)	Yes	0	4		36	0.625					9.78	50.58							No	Orthogonal (TN78E)	1355	0.99	1342	Frame Failure/ Displacement > 5'					

Table 2.1 Dataset of pushover results

PLATFORM INFORMATION							JACKET INFORMATION								PILES INFORMATION							DECK INFORMATION					ASSESSMENT INFORMATION																
Platform ID	Push-Over ID	Software	Year Installed	Location	Orientation wrt True North (TN)	Water Depth	Number of Legs	Number of Bays	Long. Batter	Trans. Batter	Long. Bracing (SD,X,K1,K2)	Trans. Bracing (SD,X,K1,K2)	OverLap (K-Joints) (Yes/No/NA)	Joint Can (Yes/No)	Piles Grouted (Yes/No)	Number of Skirt Piles	Number of Leg Piles	Actual Pile Penetration (ft)	Pile OD (in)	Pile WT (in)	Number of Conductors	Deck Size	Deck Leg Spacing	Number of Deck Elevations	Air Gap (ft)	Lower Deck Elev. (ft)	Wave Height (ft)	Time Period (sec)	Current (knot)	Storm Surge (ft)	Wind Speed (knot)	Deck Weight (kips)	Wave in Deck (Yes/No)	Direction of Wave	API 100-Year Base Shear	RSR	Ultimate Base Shear (kips)	Failure Mechanism	BS at First Member Yield	Member Type (Tension,Compression)	Defl. at First Yield (in)	Defl. at Ultimate Load (in)	Node defl. Measured
P26A	P26A-NF-01	SACS	1969	Gulf of Mexico	TN	180	4	5	1in 7	0	K1,K2	K1,K2	Yes	Yes	Yes	12	4	340	48 (2) 26 (12)		12			2			68	13.5	3.9 (fps)	3	143 (fps)			West	2170	2.10	4560	Foundation Axial Capacity Exceeded. Pile Plasticity					
P26B	P26B-NF-01	SACS	1969	Gulf of Mexico	TN	180	4	5	1in 7	0	K1,K2	K1,K2	Yes	Yes	Yes	12	4	340	48 (2) 26 (12)		22			2			68	13.5	3.9 (fps)	3	143 (fps)			West	2770	1.38	3820	Foundation Axial Capacity Exceeded. Pile Plasticity					
P26C	P26C-NF-01	SACS	1969	Gulf of Mexico	TN	180	4	5	1in 7	0	K1,K2	K1,K2	Yes	Yes	Yes	12	4	340	48 (2) 26 (12)		28			2			57.6	13.5	3.9 (fps)	3	143 (fps)			North	3350	1.51	5070	Foundation Axial Capacity Exceeded. Pile Plasticity					
P26C	P26C-NF-02	SACS	1969	Gulf of Mexico	TN	180	4	5	1in 7	0	K1,K2	K1,K2	Yes	Yes	Yes	12	4	340	48 (2) 26 (12)		28			2			64.6	13.5	3.9 (fps)	3	143 (fps)			NorthWest	3180	1.45	4610	Foundation Axial Capacity Exceeded. Pile Plasticity					
P26C	P26C-NF-03	SACS	1969	Gulf of Mexico	TN	180	4	5	1in 7	0	K1,K2	K1,K2	Yes	Yes	Yes	12	4	340	48 (2) 26 (12)		28			2			68	13.5	3.9 (fps)	3	143 (fps)			West	3120	1.20	3740	Foundation Axial Capacity Exceeded.					
P31	P31-NF-01	SACS	1964	Gulf of Mexico		170	4	6	1 in 8.5	1 in 8.5	K1,X	K1,X	Yes	Yes	Yes	0	4	240	30	0.75 (ML)	0	24'x56' (CD) 56'x56' (MD)		2	-0.15	38.25	62.3						Yes	EndOn	1298	0.83	1080	Hinging of Platform Piles					
P31	P31-NF-02	SACS	1964	Gulf of Mexico		170	4	6	1 in 8.5	1 in 8.5	K1,X	K1,X	Yes	Yes	Yes	0	4	240	30	0.75 (ML)	0	24'x56' (CD) 56'x56' (MD)		2	-0.15	38.25	62.3						Yes	Diagonal			1060	Hinging of Platform Piles					
P31	P31-NF-03	SACS	1964	Gulf of Mexico		170	4	6	1 in 8.5	1 in 8.5	K1,X	K1,X	Yes	Yes	Yes	0	4	240	30	0.75 (ML)	0	24'x56' (CD) 56'x56' (MD)		2	-0.15	38.25	62.3						Yes	Broadside	573	1.88	1080	Hinging of Platform Piles					
P36	P36-NF-01	CAP	1981	Gulf of Mexico	N80W	137	4	3			SD	SD	NA	Yes	No	0	4				6													EndOn	1176	1.64	1923	Pile Hinge					
P36	P36-NF-02	CAP	1981	Gulf of Mexico	N80W	137	4	3			SD	SD	NA	Yes	No	0	4				6													Diagonal	906	2.11	1915	Pile Hinge					
P42	P42-NF-01	SACS	1963	Gulf of Mexico	N15W	144	4	4	1 in 10	1 in 10	K1,X	K1,X	No	Yes	No	0	4	155	30	0.75	0	52'x43' (CD) 72'x52' (MD)		2	1.8	39	57.5	12.6	1.87	2.97	74		No	EndOn	784	1.23	966	Piles Plunge				16.5	
P42	P42-NF-02	SACS	1963	Gulf of Mexico	N15W	144	4	4	1 in 10	1 in 10	K1,X	K1,X	No	Yes	No	0	4	155	30	0.75	0	52'x43' (CD) 72'x52' (MD)		2	1.8	39	50	11.9	1.55	2.2	65		No	Diagonal	1212	0.71	859	Piles Plunge				11	
P42	P42-NF-03	SACS	1963	Gulf of Mexico	N15W	144	4	4	1 in 10	1 in 10	K1,X	K1,X	No	Yes	No	0	4	155	30	0.75	0	52'x43' (CD) 72'x52' (MD)		2	1.8	39	50	11.9	1.55	2.2	65		No	Broadside	1299	0.76	982	Piles Plunge				14	
P49	P49-NF-01	SACS	1964	Gulf of Mexico	N45W	140	4	5	1 in 9	1 in 9	SD,K2	K2	Yes	Yes	Yes	0	4	190	30	1.5 (ML)	0	47.5'x61.75' (CD) 47'x52' (MD)		2	-0.7	36.5	55	12.4	1.75	2.7	71		Yes	EndOn	787	1.40	1101	Piles Plunge				6.25	
P49	P49-NF-02	SACS	1964	Gulf of Mexico	N45W	140	4	5	1 in 9	1 in 9	SD,K2	K2	Yes	Yes	Yes	0	4	190	30	1.5 (ML)	0	47.5'x61.75' (CD) 47'x52' (MD)		2	-0.7	36.5	57.5	12.6	1.87	2.97	74		Yes	Diagonal	1384	0.86	1193	Piles Plunge				13	
P49	P49-NF-03	SACS	1964	Gulf of Mexico	N45W	140	4	5	1 in 9	1 in 9	SD,K2	K2	Yes	Yes	Yes	0	4	190	30	1.5 (ML)	0	47.5'x61.75' (CD) 47'x52' (MD)		2	-0.7	36.5	55	12.4	1.75	2.7	71		Yes	Broadside	1548	0.70	1083	Piles Plunge				6.25	
P50	P50-NF-01	CAP	1969	Gulf of Mexico	N12E	61	4	3	1 in 8	1 in 8	K1	K1		No	Yes	0	4																	Orthogonal	1365	1.45	1984	Frame Failure/ Displacement > 5'					
P56	P56-NF-01	ABAQUS	1998	Norh Sea	N9W	475.716	4	2	1 in 17.5	1 in 17.5	x	x	NA	Yes	Yes	0	16	213.252	96.136		22	164.04x98.42ft		9		74.474	92.847	14.4	2.7195		106.64	28399.8	No	S	9888	2.04	20152	Compression Member Buckle	10976				
P57	P57-NF-01	ABAQUS	1988	Norh Sea	N24E	164.04	4	2	1 in 11	1 in 11	k1	k1	no	Yes	Yes	0	4	150.9168	72.063	2.561	7	72.18x59.05ft		2		70.537	61.679	13.9	3.22455	7.0209	79.643	2552	No	E	6744	1.70	11458	Compression Member Buckle	12014				
P57	P57-NF-02	ABAQUS	1988	Norh Sea	N24E	164.04	4	2	1 in 11	1 in 11	k1	k1	no	Yes	Yes	0	4	150.9168	72.063	2.561	7	72.18x59.05ft		2		70.537	61.679	13.9	3.22455	7.0209	79.643	2552	No	S	7194	2.31	16625	Compression Member Buckle	10575				
6-LEG																																											
P35	P35-NF-01	SACS	1966	Gulf of Mexico	N37W	130	6	4	1 in 10	1 in 10	SD	K2	Yes	Yes	Yes	0	6	165	36	1.25 (ML)	8	20'x31.67' (SD) 45'x97.5' (CD) 45'x97.5' (MD)		3	0.73	37.33	62.5	13	2.08	3.52	80		No	EndOn	1629	1.69	2760	Piles Plunge				13.7	
P35	P35-NF-02	SACS	1966	Gulf of Mexico	N37W	130	6	4	1 in 10	1 in 10	SD	K2	Yes	Yes	Yes	0	6	165	36	1.25 (ML)	8	20'x31.67' (SD) 45'x97.5' (CD) 45'x97.5' (MD)		3	0.73	37.33	57.5	12.6	1.87	2.97	74		No	Diagonal	2842	0.81	2290	Piles Plunge				14.5	
P35	P35-NF-03	SACS	1966	Gulf of Mexico	N37W	130	6	4	1 in 10	1 in 10	SD	K2	Yes	Yes	Yes	0	6	165	36	1.25 (ML)	8	20'x31.67' (SD) 45'x97.5' (CD) 45'x97.5' (MD)		3	0.73	37.33	57.5	12.6	1.87	2.97	74		No	Broadside	2509	1.03	2581	Piles Plunge				9	
P51	P51-NF-01	SAFJAC	1968	Gulf of Mexico	N45E	118	6	3	0		X	X	NA	Yes	No (C1 leg-Yes)	0	6	105	36					2										EndOn	1190	2.72	3237						
P51	P51-NF-02	SAFJAC	1968	Gulf of Mexico	N45E	118	6	3	0		X	X	NA	Yes	No (C1 leg-Yes)	0	6	105	36					2										Diagonal	1412	2.80	3954						
8 LEG																																											
P10	P10-NF-01		1972	Gulf of Mexico	N10W	255	8	6			SD	K1,K2			No	0	8	360-312	42	2.5 (ML)	21	136'x72'		2	<5.6	45.5 (TOS)	59	12.5	1.8		70	8224	No	195 wrt X-axis	3736	1.18	4425	Jacket	3856				Deck Node 1032
P10	P10-NF-02		1972	Gulf of Mexico	N10W	255	8	6			SD	K1,K2			No	0	8	360-312	42	2.5 (ML)	21	136'x72'		2	<5.6	45.5 (TOS)	53.1	12.5	1.8		70	8224	No	240 wrt X-axis	4746	1.26	5991	Jacket	5392				Deck Node 1032
P10	P10-NF-03		1972	Gulf of Mexico	N10W	255	8	6			SD	K1,K2			No	0	8	360-312	42	2.5 (ML)	21	136'x72'		2	<5.6	45.5 (TOS)	58.02	12.5	1.8		70	8224	No	180 wrt X-axis	3314	1.31	4338	Jacket	3789				Deck Node 1032
P10	P10-NF-04		1972	Gulf of Mexico	N10W	255	8	6			SD	K1,K2			No	0	8	360-312	42	2.5 (ML)	21	136'x72'		2	<5.6	45.5 (TOS)	47.2	12.5	1.8		70	8224	No	270 wrt X-axis	4223	1.39	5886	The platform response was still in linear mode.					Deck Node 1032
P11	P11-NF-01	CAP	1973	Gulf of Mexico	N20W	263	8	5	1 in 10	1 in 10	SD	K2	Yes	Yes	Yes	0	8	300	48	2.0 (ML)	18	166'x76'		2	6.8	47	72	14.3	2.26		85		No	Broadside	5256	1.20	6298	Jacket. Buckling of K-braces and yielding in legs.	6298	Compression		36	
P11	P11-NF-02	CAP	1973	Gulf of Mexico	N20W	263	8	5	1 in 10	1 in 10	SD	K2	Yes	Yes	Yes	0	8	300	48(P) 42(S)	2.0 (ML)	18	166'x76'		2	6.8	47	68.4	14.18	2.05		85		No	EndOn	4154	1.12	4660	Jacket Diagonals	4302	Compression		62	
P11	P11-NF-03	CAP	1973	Gulf of Mexico	N20W	263	8	5	1 in 10	1 in 10	SD	K2	Yes	Yes	Yes	0	8	300	48	2.0 (ML)	18	166'x76'		2	6.8	47	72	14.31	2.28		85		No	Diagonal	5232	1.26	6587	Jacket Diagonals	6108	Compression		75	
P12	P12-NF-01	SACS	1973	Gulf of Mexico	N30W	300	8	6	1 in 7.86	1 in 7.86	SD,X	K1,K2			Yes	4	8	320-340	48		24				5.7	46.5	54.9	12.5	1.80	3.5	70		No	EndOn	4726	3.18	15029	Jacket	5780			15	

Table 2.1 Dataset of pushover results

PLATFORM INFORMATION							JACKET INFORMATION								PILES INFORMATION							DECK INFORMATION					ASSESSMENT INFORMATION																
Platform ID	Push-Over ID	Software	Year Installed	Location	Orientation wrt True North (TN)	Water Depth	Number of Legs	Number of Bays	Long. Batter	Trans. Batter	Long. Bracing (SD,X,K1,K2)	Trans. Bracing (SD,X,K1,K2)	OverLap (K-Joints) (Yes/No/NA)	Joint Can (Yes/No)	Piles Grouted (Yes/No)	Number of Skirt Piles	Number of Leg Piles	Actual Pile Penetration (ft)	Pile OD (in)	Pile WT (in)	Number of Conductors	Deck Size	Deck Leg Spacing	Number of Deck Elevations	Air Gap (ft)	Lower Deck Elev. (ft)	Wave Height (ft)	Time Period (sec)	Current (knot)	Storm Surge (ft)	Wind Speed (knot)	Deck Weight (kips)	Wave in Deck (Yes/No)	Direction of Wave	API 100-Year Base Shear	RSR	Ultimate Base Shear (kips)	Failure Mechanism	BS at First Member Yield	Member Type (Tension,Compression)	Defl. at First Yield (in)	Defl. at Ultimate Load (in)	Node defl. Measured
P12	P12-NF-02	SACS	1973	Gulf of Mexico	N30W	300	8	6	1 in 7.86	1 in 7.86	SD,X	K1,K2			Yes	4	8	320-340	48(P) 42(S)		24				5.7	46.5	61	12.5	1.80	3.5	70		No	Broadside	4288	3.24	13894	Jacket	5300			14.5	
P15	P15-NF-01		1978	Gulf of Mexico	N	343	8	6			SD,X	X			No	8	8								<10.2	51 (TOS)							No	Broadside			20700	Frame Failure/ Pile Hinge					
P15	P15-NF-02		1978	Gulf of Mexico	N	343	8	6			SD,X	X			No	8	8								<10.2	51 (TOS)							No	Diagonal			17900	Frame Failure					
P18	P18-NF-01		1969	Gulf of Mexico	N36W	247	8	5			SD	K1,K2		Yes	No	0	8	240	42	1.375	14	136'x72' (PD) 136'x72' (DD)		2	7.3	47.5	59.4	12.5	1.8		70		No	169 (PLATFORM)	3143	1.14	3592	Jacket	3547				
P18	P18-NF-02		1969	Gulf of Mexico	N36W	247	8	5			SD	K1,K2		Yes	No	0	8	240	42	1.375	14	136'x72' (PD) 136'x72' (DD)		2	7.3	47.5	57.9	12.5	1.8		70		No	180	3346	1.11	3719	Jacket	3641				
P18	P18-NF-03		1969	Gulf of Mexico	N36W	247	8	5			SD	K1,K2		Yes	No	0	8	240	42	1.375	14	136'x72' (PD) 136'x72' (DD)		2	7.3	47.5	53.5	12.5	1.8		70		No	214	4044	1.11	4470	Jacket	4339				
P18	P18-NF-04		1969	Gulf of Mexico	N36W	247	8	5			SD	K1,K2		Yes	No	0	8	240	42	1.375	14	136'x72' (PD) 136'x72' (DD)		2	7.3	47.5	43.8	12.5	1.8		70		No	270	3254	1.50	4876	Jacket	4861				
P19	P19-NF-01	SAFJAC	1979	Gulf of Mexico		125	8	3			SD,X	K2			No									2		52.0						3281		Broadside	1843	5.01	9237	Yielding in Piles and in K-framing in Rows 1 and 2					
P19	P19-NF-02	SAFJAC	1979	Gulf of Mexico		125	8	3			SD,X	K2			No									2		52.0						3281		Diagonal	1785	5.17	9225	Initial yielding in Piles with load redistribution causing yielding & buckling in Row					
P19	P19-NF-03	SAFJAC	1979	Gulf of Mexico		125	8	3			SD,X	K2			No									2		52.0						3281		EndOn	1669	4.20	7007	Yielding in lower bay X-braces in Rows A &B and Pile/Soil T-Z highly					
P24	P24-NF-01	CAP	1967	Gulf of Mexico	N30W	340	8	4	1 in 10	1 in 10	SD,K3	SD,X,K3			No (Skt. Pls-Yes)	8	8	180	48		18				3.2	44	61.5	12.5	2.13	2.5	70	7433	No	EndOn	5567	1.30	7238	Jacket					
P24	P24NF-02	CAP	1967	Gulf of Mexico	N30W	340	8	4	1 in 10	1 in 10	SD,K3	SD,X,K3			No	8	8	180	48		18				3.2	44	58.4	12.5	2.45	2.5	70	7433	No	Diagonal	4738	1.92	9100	Pile					
P24	P24-NF-03	CAP	1967	Gulf of Mexico	N30W	340	8	4	1 in 10	1 in 10	SD,K3	SD,X,K3			No	8	8	180	48		18				3.2	44	52.3	12.5	2.06	2.5	70	7433	No	Broadside	3307	2.76	9140	Pile					
P27	P27-NF-01			Gulf of Mexico	N19E	310	8	5	1 in 8	1 in 8	SD,X	X	NA	Yes	No	0	8		60		10				11.7	52.5	58.1	13		3			No	EndOn	4528	2.50	11320	Jacket	5886			30	
P27	P27-NF-02			Gulf of Mexico	N19E	310	8	5	1 in 8	1 in 8	SD,X	X	NA	Yes	No	0	8		60		10				11.7	52.5	63.5	13		3			No	Diagonal	4400	2.30	10120	Jacket	5280			28.8	
P27	P27-NF-03			Gulf of Mexico	N19E	310	8	5	1 in 8	1 in 8	SD,X	X	NA	Yes	No	0	8		60		10				11.7	52.5	68.3	13		3			No	Broadside	4539	2.80	12710	Jacket	8171			36	
P28	P28-NF-01	SACS	1957	Gulf of Mexico	N25W	140	8	5	0	1 in 15	SD	K1,X	No	Yes	Yes	0	8	175	30	0.75 (ML)	10	40x80(SD) 40x112(CD) 45x105(MD)		3	17	54.25	45	11.5	1.35	1.85	59		No	EndOn	1889	0.75	1420	Piles Pull Out					
P28	P28-NF-02	SACS	1957	Gulf of Mexico	N25W	140	8	5	0	1 in 15	SD	K1,X	No	Yes	Yes	0	8	175	30	0.75 (ML)	10	40x80(SD) 40x112(CD) 45x105(MD)		3	17	54.25	45	11.5	1.35	1.85	59		No	Diagonal	2639	0.49	1280	Piles Pull Out					
P28	P28-NF-03	SACS	1957	Gulf of Mexico	N25W	140	8	5	0	1 in 15	SD	K1,X	No	Yes	Yes	0	8	175	30	0.75 (ML)	10	40x80(SD) 40x112(CD) 45x105(MD)		3	17	54.25	45	11.5	1.35	1.85	59		No	Broadside	2612	0.56	1459	Piles Pull Out					
P33	P33-NF-01	SACS	1962	Gulf of Mexico	N35W	145	8	4	1 in 10	1 in 10	SD	K1,X	Yes	Yes	Yes	0	8	240	33	1.11 (ML)	8	22'x34.3' (SC) 40'X115' (CD) 40'x148' (MD)		3	-8.2	29	52.5	12.2	1.67	2.48	68		Yes	EndOn	2257	0.95	2142	Piles Plunge	1224		5.9	12	
P33	P33-NF-02	SACS	1962	Gulf of Mexico	N35W	145	8	4	1 in 10	1 in 10	SD	K1,X	Yes	Yes	Yes	0	8	240	33	1.11 (ML)	8	22'x34.3' (SC) 40'X115' (CD) 40'x148' (MD)		3	-8.2	29	52.5	12.2	1.67	2.48	68		Yes	Diagonal	3839	0.56	2142	Piles Plunge	1823		9	11.5	
P33	P33-NF-03	SACS	1962	Gulf of Mexico	N35W	145	8	4	1 in 10	1 in 10	SD	K1,X	Yes	Yes	Yes	0	8	240	33	1.11 (ML)	8	22'x34.3' (SC) 40'X115' (CD) 40'x148' (MD)		3	-8.2	29	55	12.4	1.75	2.7	71		Yes	Broadside	3388	0.82	2789	Piles Plunge	2454		12	17	
P34	P34-NF-01	SACS	1969	Gulf of Mexico	N35W	176	8	5	1 in 9	1 in 9	SD,K2	K2	Yes	Yes	Yes	0	8	265	36	1.375	8	22'x41' (SC) 43'X118' (CD) 43'x151' (MD)		3	-5.4	33	62.5	13	2.08	3.52	80		Yes	EndOn	3546	0.91	3243	Piles Hinge	2915		14.5	17.5	
P34	P34-NF-02	SACS	1969	Gulf of Mexico	N35W	176	8	5	1 in 9	1 in 9	SD,K2	K2	Yes	Yes	Yes	0	8	265	36	1.375	8	22'x41' (SC) 43'X118' (CD) 43'x151' (MD)		3	-5.4	33	60	12.8	1.95	3.2	77		Yes	Diagonal	4081	0.85	3476	Piles Hinge	2964		12.5	17	
P34	P34-NF-03	SACS	1969	Gulf of Mexico	N35W	176	8	5	1 in 9	1 in 9	SD,K2	K2	Yes	Yes	Yes	0	8	265	36	1.375	8	22'x41' (SC) 43'X118' (CD) 43'x151' (MD)		3	-5.4	33	60	12.8	1.95	3.2	77		Yes	Broadside	3611	1.04	3760	Piles Hinge	3459		13	15	
P37	P37-NF-01	SACS	1967	Gulf of Mexico		107	8	4	1 in 10	1 in 10	SD,K2	K2	Yes	Yes	Yes	0	8	150	36	1.375 (ML)	12	30.5'x42' (SD) 46.'x133' (CD) 46'x151' (MD)		3	1.95	36.75	65	13.3	2.18	3.8	83		No	EndOn	3941	1.31	5178	Piles Plunge	4808		11	13	
P37	P37-NF-02	SACS	1967	Gulf of Mexico		107	8	4	1 in 10	1 in 10	SD,K2	K2	Yes	Yes	Yes	0	8	150	36	1.375 (ML)	12	30.5'x42' (SD) 46.'x133' (CD) 46'x151' (MD)		3	1.95	36.75	57.5	12.6	1.87	2.97	74		No	Diagonal			4171	Piles Plunge	4091		7	7.5	
P37	P37-NF-03	SACS	1967	Gulf of Mexico		107	8	4	1 in 10	1 in 10	SD,K2	K2	Yes	Yes	Yes	0	8	150	36	1.375 (ML)	12	30.5'x42' (SD) 46.'x133' (CD) 46'x151' (MD)		3	1.95	36.75	60	12.8	1.95	3.2	77		No	Broadside	2169	2.48	5377	Piles Plunge	4993		11.5	13	
P38	P38-NF-01	SACS	1961	Gulf of Mexico	N15W	137	8	4	0	1 in 12	SD	K1,X	No	Yes	No	0	8	197	30	0.75 (ML)	8	22'x32 (SD) 46'x150' (CD) 46'x150' (MD)		3	-2.7	34.5	52.5	12.2	1.67	2.48	68		Yes	EndOn	2346	0.84	1973	Hinging of Platform Piles	1835		18	21.5	
P38	P38-NF-02	SACS	1961	Gulf of Mexico	N15W	137	8	4	0	1 in 12	SD	K1,X	No	Yes	No	0	8	197	30	0.75 (ML)	8	22'x32 (SD) 46'x150' (CD) 46'x150' (MD)		3	-2.7	34.5	52.5	12.2	1.67	2.48	68		Yes	Diagonal	3100	0.77	2389	Hinging of Platform Piles	2012		17	23.5	
P38	P38-NF-03	SACS	1961	Gulf of Mexico	N15W	137	8	4	0	1 in 12	SD	K1,X	No	Yes	No	0	8	197	30	0.75 (ML)	8	22'x32 (SD) 46'x150' (CD) 46'x150' (MD)		3	-2.7	34.5	55	12.4	1.75	2.7	71		Yes	Broadside	3260	0.85	2778	Hinging of Platform Piles	2506		18	21	
P40	P40-NF-01	SACS	1963	Gulf of Mexico	N15W	180	8	5	1 in 10	1 in 10	SD,X	K1,X	Yes	Yes	Yes	0	8	180	30	1.0 (ML)	12				-1.4	37	60.85						Yes	EndOn	2565	1.32	3387	Piles Plunge	2568		11	23	
P40	P40-NF-02	SACS	1963	Gulf of Mexico	N15W	180	8	5	1 in 10	1 in 10	SD,X	K1,X	Yes	Yes	Yes	0	8	180	30	1.0 (ML)	12				-1.4	37	60.85						Yes	Diagonal	3843	0.88	3384	Piles Plunge	3288		12.5	14	
P40	P40-NF-03	SACS	1963	Gulf of Mexico	N15W	180	8	5	1 in 10	1 in 10	SD,X	K1,X	Yes	Yes	Yes	0	8	180	30	1.0 (ML)	12				-1.4	37	60.85						Yes	Broadside	3959	0.93	3687	Piles Plunge	2947		11.5	14	

Table 2.1 Dataset of pushover results

PLATFORM INFORMATION							JACKET INFORMATION								PILES INFORMATION							DECK INFORMATION					ASSESSMENT INFORMATION																
Platform ID	Push-Over ID	Software	Year Installed	Location	Orientation wrt True North (TN)	Water Depth	Number of Legs	Number of Bays	Long. Batter	Trans. Batter	Long. Bracing (SD,X,K1,K2)	Trans. Bracing (SD,X,K1,K2)	OverLap (K-Joints) (Yes/No/NA)	Joint Can (Yes/No)	Piles Grouted (Yes/No)	Number of Skirt Piles	Number of Leg Piles	Actual Pile Penetration (ft)	Pile OD (in)	Pile WT (in)	Number of Conductors	Deck Size	Deck Leg Spacing	Number of Deck Elevations	Air Gap (ft)	Lower Deck Elev. (ft)	Wave Height (ft)	Time Period (sec)	Current (knot)	Storm Surge (ft)	Wind Speed (knot)	Deck Weight (kips)	Wave in Deck (Yes/No)	Direction of Wave	API 100-Year Base Shear	RSR	Ultimate Base Shear (kips)	Failure Mechanism	BS at First Member Yield	Member Type (Tension,Compression)	Defl. at First Yield (in)	Defl. at Ultimate Load (in)	Node defl. Measured
P41	P41-NF-01	SACS	1968	Gulf of Mexico		137	8	4			SD, X	K1,X		Yes		0	8				0	10'x28.75' (SD) 40'x115' (CD) 70'x161.8' (MD)		3	-14.8	22.41	55		1.75	2.7	71			EndOn	2787	0.64	1775	Piles Yield Below Mudline				11	
P41	P41-NF-02	SACS	1968	Gulf of Mexico		137	8	4			SD, X	K1,X		Yes		0	8				0	10'x28.75' (SD) 40'x115' (CD) 70'x161.8' (MD)		3	-14.8	22.41	55		1.75	2.7	71			Diagonal			1963	Piles Plunge				12.5	
P41	P41-NF-03	SACS	1968	Gulf of Mexico		137	8	4			SD, X	K1,X		Yes		0	8				0	10'x28.75' (SD) 40'x115' (CD) 70'x161.8' (MD)		3	-14.8	22.41	52.5		1.67	2.48	68			Broadside	1764	1.31	2309	Piles Plunge				17	
P44	P44-NF-01	USFOS	1964	Gulf of Mexico	N1W	118	8	4	1 in 8	1 in 8	SD	K1,K2			Yes	0	8							2	-1.25	34.75								Broadside	4200 (interpolated from Andrew	1.05	4423	Frame Failure/ Displacement > 5'	900				
P45	P45-NF-01	SACS	1962	Gulf of Mexico	N35W	140	8	4	1 in 10	1in 10	SD,X	K1,X	No	Yes	No	0	8	260	30	1.75 (ML)	8	22'X34.3 (SD) 42.8'X117.8' (CD) 42.8'X148' (MD)		3	-11.2	26	60	12.8	1.95	3.2	77		Yes	EndOn	3591	0.91	3275	Piles Hinge				35	
P45	P45-NF-02	SACS	1962	Gulf of Mexico	N35W	140	8	4	1 in 10	1in 10	SD,X	K1,X	No	Yes	No	0	8	260	30	1.75 (ML)	8	22'X34.3 (SD) 42.8'X117.8' (CD) 42.8'X148' (MD)		3	-11.2	26	57.5	12.6	1.87	2.97	74		Yes	Diagonal	4598	0.69	3162	Piles Hinge				39	
P45	P45-NF-03	SACS	1962	Gulf of Mexico	N35W	140	8	4	1 in 10	1in 10	SD,X	K1,X	No	Yes	No	0	8	260	30	1.75 (ML)	8	22'X34.3 (SD) 42.8'X117.8' (CD) 42.8'X148' (MD)		3	-11.2	26	52.5	12.2	1.67	2.48	68		Yes	Broadside	3591	0.84	3028	Piles Plunge				33	
P46	P46-NF-01	SACS	1964	Gulf of Mexico	N35W	140	8	4	1 in 10	1 in 10	SD,X	K1,X	Yes	Yes	No	0	8	180	30	1 (ML)	16	22'X60' (SD) 43'X115' (CD) 43'X148' (MD)		3	-11.2	26	50	11.9	1.55	2.2	65		Yes	EndOn	3921	0.66	2607	Foundation Failure				17	
P46	P46-NF-02	SACS	1964	Gulf of Mexico	N35W	140	8	4	1 in 10	1 in 10	SD,X	K1,X	Yes	Yes	No	0	8	180	30	1 (ML)	16	22'X60' (SD) 43'X115' (CD) 43'X148' (MD)		3	-11.2	26	45	11.5	1.35	1.85	59		Yes	Diagonal	4170	0.53	2214	Foundation Failure				14	
P46	P46-NF-03	SACS	1964	Gulf of Mexico	N35W	140	8	4	1 in 10	1 in 10	SD,X	K1,X	Yes	Yes	No	0	8	180	30	1 (ML)	16	22'X60' (SD) 43'X115' (CD) 43'X148' (MD)		3	-11.2	26	47.5						Yes	Broadside	4296	0.54	2304	Foundation Failure				13	
P47	P47-NF-01	SACS	1964	Gulf of Mexico	N35W	140	8	4	1 in 10	1 in 10	SD,X	K1,X	Yes	Yes	Yes	0	8	180	30	1 (ML)	0	42.5'X117.5' (CD) 70.5'x162' (MD)		2	5.8	43	60	12.8	1.95	3.2	77		No	EndOn	2135	1.11	2364	Piles Plunge				8	
P47	P47-NF-02	SACS	1964	Gulf of Mexico	N35W	140	8	4	1 in 10	1 in 10	SD,X	K1,X	Yes	Yes	Yes	0	8	180	30	1 (ML)	0	42.5'X117.5' (CD) 70.5'x162' (MD)		2	5.8	43	55	12.4	1.75	2.7	71		No	Diagonal	2281	0.91	2078	Piles Plunge				8	
P47	P47-NF-03	SACS	1964	Gulf of Mexico	N35W	140	8	4	1 in 10	1 in 10	SD,X	K1,X	Yes	Yes	Yes	0	8	180	30	1 (ML)	0	42.5'X117.5' (CD) 70.5'x162' (MD)		2	5.8	43	57.5	12.6	1.87	2.97	74		No	Broadside	2304	0.86	1987	Piles Plunge				8.5	
P48	P48-NF-01	SACS	1966	Gulf of Mexico		141	8	4	1 in 9	1 in 9	SD,K2	K2	Yes	Yes	Yes	0	8	180	36	1.25 (ML)	16	20'x45' (SD) 45.83'x133.2' (CD) 45.83'x133.2'		3	0.13	37.33	55	12.4	1.75	2.7	71		No	EndOn	4497	0.70	3140	Piles Plunge				11.5	
P48	P48-NF-02	SACS	1966	Gulf of Mexico		141	8	4	1 in 9	1 in 9	SD,K2	K2	Yes	Yes	Yes	0	8	180	36	1.25 (ML)	16	20'x45' (SD) 45.83'x133.2' (CD) 45.83'x133.2'		3	0.13	37.33	52.5	12.2	1.67	2.48	68		No	Diagonal			3040	Piles Plunge				9	
P48	P48-NF-03	SACS	1966	Gulf of Mexico		141	8	4	1 in 9	1 in 9	SD,K2	K2	Yes	Yes	Yes	0	8	180	36	1.25 (ML)	16	20'x45' (SD) 45.83'x133.2' (CD) 45.83'x133.2'		3	0.13	37.33	52.5	12.2	1.67	2.48	68		No	Broadside	2258	1.48	3344	Piles Plunge				9	
P52	P52-NF-01	KARMA	1965	Gulf of Mexico	N2.8E	160	8	5	1 in 6	1 in 20	SD	K2		Yes	No(Main) Yes (Skirt)	10	8	182	30		11	15'x32.67' (SD) 40'x98' (CD) 66'x114' (MD)		3	<2.2	40 (TOS)	53.6		0.2			1383	No	EndOn (0)	2956	1.80	5315	Foundation failure followed by failure of piles.					
P52	P52-NF-02	KARMA	1965	Gulf of Mexico	N2.8E	160	8	5	1 in 6	1 in 20	SD	K2		Yes	No(Main) Yes (Skirt)	10	8	182	30		11	15'x32.67' (SD) 40'x98' (CD) 66'x114' (MD)		3	<2.2	40 (TOS)	44.2		0.2			1383	No	Diagonal (45)	2297	2.27	5220	Foundation failure followed by failure of piles.					
P52	P52-NF-03	KARMA	1965	Gulf of Mexico	N2.8E	160	8	5	1 in 6	1 in 20	SD	K2		Yes	No(Main) Yes (Skirt)	10	8	182	30		11	15'x32.67' (SD) 40'x98' (CD) 66'x114' (MD)		3	<2.2	40 (TOS)	44.2		0.2			1383	No	Broadside (90)	1920	2.72	5215	Foundation failure followed by failure of piles.					
P52	P52-NF-04	KARMA	1965	Gulf of Mexico	N2.8E	160	8	5	1 in 6	1 in 20	SD	K2		Yes	No(Main) Yes (Skirt)	10	8	182	30		11	15'x32.67' (SD) 40'x98' (CD) 66'x114' (MD)		3	<2.2	40 (TOS)	44.2		0.2			1383	No	Diagonal (135)	1977	2.58	5104	Foundation failure followed by failure of piles.					
P52	P52-NF-05	KARMA	1965	Gulf of Mexico	N2.8E	160	8	5	1 in 6	1 in 20	SD	K2		Yes	No(Main) Yes (Skirt)	10	8	182	30		11	15'x32.67' (SD) 40'x98' (CD) 66'x114' (MD)		3	<2.2	40 (TOS)	47.3		0.2			1383	No	EndOn (180)	2352	2.27	5346	Foundation failure followed by failure of piles.					
P52	P52-NF-06	KARMA	1965	Gulf of Mexico	N2.8E	160	8	5	1 in 6	1 in 20	SD	K2		Yes	No(Main) Yes (Skirt)	10	8	182	30		11	15'x32.67' (SD) 40'x98' (CD) 66'x114' (MD)		3	<2.2	40 (TOS)	56.8		2.09			1383	No	Diagonal (225)	4707	1.17	5484	Foundation failure followed by failure of piles.					
P52	P52-NF-07	KARMA	1965	Gulf of Mexico	N2.8E	160	8	5	1 in 6	1 in 20	SD	K2		Yes	No(Main) Yes (Skirt)	10	8	182	30		11	15'x32.67' (SD) 40'x98' (CD) 66'x114' (MD)		3	<2.2	40 (TOS)	63.1		2.09			1383	No	Broadside (270)	5932	0.94	5552	Foundation failure followed by failure of piles.					
P52	P52-NF-08	KARMA	1965	Gulf of Mexico	N2.8E	160	8	5	1 in 6	1 in 20	SD	K2		Yes	No(Main) Yes (Skirt)	10	8	182	30		11	15'x32.67' (SD) 40'x98' (CD) 66'x114' (MD)		3	<2.2	40 (TOS)	63.1		2.09			1383	No	Diagonal (290)	5724	0.96	5476	Foundation failure followed by failure of piles.					
P52	P52-NF-09	KARMA	1965	Gulf of Mexico	N2.8E	160	8	5	1 in 6	1 in 20	SD	K2		Yes	No(Main) Yes (Skirt)	10	8	182	30		11	15'x32.67' (SD) 40'x98' (CD) 66'x114' (MD)		3	<2.2	40 (TOS)	59.9		2.09			1383	No	Diagonal (315)	4721	1.14	5380	Foundation failure followed by failure of piles.					
P53	P53-NF-01		1965	Gulf of Mexico		223	8	5	1 in 10	1 in 10	SD	SD,K3		Yes			8									40								Diagonal		0.60	3522	Jacket, Pile				30	Deck. (+)41'
P53	P53-NF-02		1965	Gulf of Mexico		223	8	5	1 in 10	1 in 10	SD	SD,K3		Yes			8									40								Broadside		0.60	3471	Jacket (local member and joint can punching shear failures)				24	Deck. (+)41'
P54	P54-NF-01	SACS	1978	Gulf of Mexico		211	8	4	1 in 8	1 in 8	SD	SD	NA	Yes	Yes	0	8	330	42	1.75 (ML)	24	55'x62.5' (SD) 70'x165' (CD) 70'x165' (MD)		3	0.4	40	75	14.1	2.6	5.1	94			EndOn	4946	1.55	7685	Piles Plunge	6650		20	22	
P54	P54-NF-02	SACS	1978	Gulf of Mexico		211	8	4	1 in 8	1 in 8	SD	SD	NA	Yes	Yes	0	8	330	42	1.75 (ML)	24	55'x62.5' (SD) 70'x165' (CD) 70'x165' (MD)		3	0.4	40	70	13.7	2.4	4.4	88			Diagonal			6806	Piles Plunge	5672		18	20	
P54	P54-NF-03	SACS	1978	Gulf of Mexico		211	8	4	1 in 8	1 in 8	SD	SD	NA	Yes	Yes	0	8	330	42	1.75 (ML)	24	55'x62.5' (SD) 70'x165' (CD) 70'x165' (MD)		3	0.4	40	70	13.7	2.4	4.4	88			Broadside	3133	2.25	7064	Piles Plunge				33	
P55	P55-NF-01	KARMA	1968	Gulf of Mexico	N55W	184	8	6	1 in 8	1 in 8	SD,X	K2,X		No	Yes	0	8	160	36	0.75-1.75	14	119'x70' (MD) 90'x40'(CD)		3	0.52	38.92	51.75	12.5	2.7	3	70	1521	No	EndOn	2492	1.60	3975	Foundation					
P55	P55-NF-02	KARMA	1968	Gulf of Mexico	N55W	184	8	6	1 in 8	1 in 8	SD,X	K2,X		No	Yes	0	8	160	36	0.75-1.75	14	119'x70' (MD) 90'x40'(CD)		3	0.52	38.92	57.5	12.5	3	3	70	1521	No	Diagonal1 (22.35)	2712	1.56	4219	Foundation					
P55	P55-NF-03	KARMA	1968	Gulf of Mexico	N55W	184	8	6	1 in 8	1 in 8	SD,X	K2,X		No	Yes	0	8	160	36	0.75-1.75	14	119'x70' (MD) 90'x40'(CD)		3	0.52	38.92	57.5	12.5	3	3	70	1521	No	Diagonal	2528	1.81	4588	Foundation					
P55	P55-NF-04	KARMA	1968	Gulf of Mexico	N55W	184	8	6	1 in 8	1 in 8	SD,X	K2,X		No	Yes	0	8	160	36	0.75-1.75	14	119'x70' (MD) 90'x40'(CD)		3	0.52	38.92	54.63	12.5	2.85	3	70	1521	No	Broadside	2176	2.19	4767	Foundation					

Table 2.1 Dataset of pushover results

PLATFORM INFORMATION							JACKET INFORMATION								PILES INFORMATION							DECK INFORMATION					ASSESSMENT INFORMATION																
Platform ID	**Push-Over ID**	**Software**	**Year Installed**	**Location**	**Orientation wrt True North (TN)**	**Water Depth**	**Number of Legs**	**Number of Bays**	**Long. Batter**	**Trans. Batter**	**Long. Bracing** (SD,X,K1,K2)	**Trans. Bracing** (SD,X,K1,K2)	**OverLap (K-Joints)** (Yes/No/NA)	**Joint Can** (Yes/No)	**Piles Grouted** (Yes/No)	**Number of Skirt Piles**	**Number of Leg Piles**	**Actual Pile Penetration (ft)**	**Pile OD (in)**	**Pile WT (in)**	**Number of Conductors**	**Deck Size**	**Deck Leg Spacing**	**Number of Deck Elevations**	**Air Gap (ft)**	**Lower Deck Elev. (ft)**	**Wave Height (ft)**	**Time Period (sec)**	**Current (knot)**	**Storm Surge (ft)**	**Wind Speed (knot)**	**Deck Weight (kips)**	**Wave in Deck** (Yes/No)	**Direction of Wave**	**API 100-Year Base Shear**	**RSR**	**Ultimate Base Shear (kips)**	**Failure Mechanism**	**BS at First Member Yield**	**Member Type** (Tension,Compression)	**Defl. at First Yield (in)**	**Defl. at Ultimate Load (in)**	**Node defl. Measured**
P58	P58-NF-01	ABAQUS	1976	North Sea	N45W	360.888	8	4	0	1 in 5	k1	k2	no	Yes	Yes	24	4	150.9168	60.046	3.5066	36	154.20x213.25ft		3		67.91	80.052	15.7	1.9425	3.1168	100.04	29700	No	NW	12300	3.78	46482	Compression Member Buckle	6400				
> 8 LEGS																																											
P32	P32-NF-01	SACS	1965	Gulf of Mexico		168	10	5	1 in 10	1 in 10	SD	K2	Yes	Yes	Yes	0	10	270	30	1 (ML)	0			2	-0.34	38.06	62.5	13	2.08	3.52	80		Yes	EndOn	2447	0.99	2413	Piles Plunge	1957		5.9	12	
P32	P32-NF-02	SACS	1965	Gulf of Mexico		168	10	5	1 in 10	1 in 10	SD	K2	Yes		Yes	0	10	270	30	1 (ML)	0			2	-0.34	38.06	62.5	13	2.08	3.52	80		Yes	Diagonal			2598	Piles Plunge	2362		9	11.5	
P32	P32-NF-03	SACS	1965	Gulf of Mexico		168	10	5	1 in 10	1 in 10	SD	K2	Yes		Yes	0	10	270	30	1 (ML)	0			2	-0.34	38.06	62.5	13	2.08	3.52	80		Yes	Broadside	1557	1.83	2853	Piles Plunge	2563		12	17	
P20	P20-NF-01	ASADS	1968	California		155	12	4			SD	SD	NA	Yes	Yes	0	12		36	1.5	39				-5.8	32						2720	Yes		3355	2.8^{F}	9394	Jacket, Piles	6039				
P21	P21-NF-01		1968	California		189	12	5	1 in 8	1in 8	SD	SD,K1			Yes	0	12	85			56				1.3	40						5200	No	Broadside	2300	2.43	5600						
P21	P21-NF-02		1968	California		189	12	5	1 in 8	1in 8	SD	SD,K1			N/A	0	12	85	40		56				1.3	40						5200	No	EndOn	2300	2.48	5700						
P29	P29-NF-01	SACS	1960/1971	Gulf of Mexico		187	8 (14)	6	1 in 10	1 in 10	SD,X	K1,X	No	Yes	Yes	0	8(14)	230	30	0.75 (ML)	16	40'x115' (CD) 55'x145' (MD)		2	-4.7	34	50	11.9	1.55	2.2	65		Yes	EndOn	5315	0.52	2780	Foundation Failure in Tripod				15	
P29	P29-NF-02	SACS	1960/1971	Gulf of Mexico		187	8 (14)	6	1 in 10	1 in 10	SD,X	K1,X	No	Yes	Yes	0	8(14)	230	30	0.75 (ML)	16	40'x115' (CD) 55'x145' (MD)		2	-4.7	34	47.5						Yes	Diagonal			2521	Foundation Failure				11	
P29	P29-NF-03	SACS	1960/1971	Gulf of Mexico		187	8 (14)	6	1 in 10	1 in 10	SD,X	K1,X	No	Yes	Yes	0	8(14)	230	30	0.75 (ML)	16	40'x115' (CD) 55'x145' (MD)		2	-4.7	34	47.5						Yes	Broadside	3168	0.85	2695	Foundation Failure				13.5	
P30	P30-NF-01	SACS	1962/1972	Gulf of Mexico		160	8 (14)	5	1 in 10	1 in 10	SD,X	K1,X	Yes	Yes	No/Yes	0	8(14)	250	30	0.75 (ML)	9	20'x63' (SD) 54'x131' (CD) 54'x131' (MD)		3	-3.8	34	55	12.4	1.75	2.7	71		Yes	EndOn	7444	0.52	3869	Hinging of Platform Piles	3405		12.5	28	
P30	P30-NF-02	SACS	1962/1972	Gulf of Mexico		160	8 (14)	5	1 in 10	1 in 10	SD,X	K1,X	Yes	Yes	No/Yes	0	8(14)	250	30	0.75 (ML)	9	20'x63' (SD) 54'x131' (CD) 54'x131' (MD)		3	-3.8	34	55	12.4	1.75	2.7	71		Yes	Diagonal			4229	Hinging of Platform Piles	3695		12.5	24	
P30	P30-NF-03	SACS	1962/1972	Gulf of Mexico		160	8 (14)	5	1 in 10	1 in 10	SD,X	K1,X	Yes	Yes	No/Yes	0	8(14)	250	30	0.75 (ML)	9	20'x63' (SD) 54'x131' (CD) 54'x131' (MD)		3	-3.8	34	55	12.4	1.75	2.7	71		Yes	Broadside	3472	1.27	4419	Hinging of Platform Piles	3944		11	22	
P39	P39-NF-01	SACS	1963/1972	Gulf of Mexico	N20W	128	8 (14)	4	1 in 10	1in 10	SD,X	K1,X	No	Yes	Yes	0	8 (14)	188	30	0.75	12	22x53 (SC) 52.5'X117.5' (CD) 42.5'x148 (MD)		3	-10.3	26	55	12.4	1.75	2.7	71		Yes	EndOn	3474	1.13	3930	Foundation Failure				11.5	
P39	P39-NF-02	SACS	1963/1972	Gulf of Mexico	N20W	128	8 (14)	4	1 in 10	1in 10	SD,X	K1,X	No	Yes	Yes	0	8 (14)	188	30	0.75	12	22x53 (SC) 52.5'X117.5' (CD) 42.5'x148 (MD)		3	-10.3	26	52.5	12.2	1.67	2.48	68		Yes	Diagonal	4784	0.78	3720	Foundation Failure				9	
P39	P39-NF-03	SACS	1963/1972	Gulf of Mexico	N20W	128	8 (14)	4	1 in 10	1in 10	SD,X	K1,X	No	Yes	Yes	0	8 (14)	188	30	0.75	12	22x53 (SC) 52.5'X117.5' (CD) 42.5'x148 (MD)		3	-10.3	26	52.5	12.2	1.67	2.48	68		Yes	Broadside	5612	0.77	4333	Foundation Failure				12.5	
P43	P43-NF-01	SACS	1960/1972	Gulf of Mexico		139	8 (14)	5	0		SD	K1,X		Yes	Yes (Tripods)	0	8(14)	206	30	0.75		120'x40' (CD) 150x40' (MD)		2	-2.6	34.6	50	11.9	1.55	2.2	65		Yes	EndOn	4954	0.56	2789	Tripod piles pull-out or plunge				13.5	
P43	P43-NF-02	SACS	1960/1972	Gulf of Mexico		139	8 (14)	5	0		SD	K1,X		Yes	Yes (Tripods)	0	8(14)	206	30	0.75		120'x40' (CD) 150x40' (MD)		2	-2.6	34.6	50	11.9	1.55	2.2	65		Yes	Diagonal			3037	Jacket and tripod piles pull-out or plunge				13	
P43	P43-NF-03	SACS	1960/1972	Gulf of Mexico		139	8 (14)	5	0		SD	K1,X		Yes	Yes (Tripods)	0	8(14)	206	30	0.75		120'x40' (CD) 150x40' (MD)		2	-2.6	34.6	52.5		1.67	2.48	68		Yes	Broadside	3059	1.06	3249	Piles Pull Out				14	
P14	P14-NF-01	ASADS	1957	Gulf of Mexico	N45E	88	16	4	0	0	X	X	NA	No	Yes	0	16	150	30	0.625	14			2	11.3	44	58	13.5	2.3		85		No	EndOn	1134	2.68	3040	Leg/Pile	726	Compression		50	
P14	P14-NF-02	ASADS	1957	Gulf of Mexico	N45E	88	16	4	0	0	X	X	NA	No	Yes	0	16	150	30	0.625	14			2	11.3	44	58	13.5	2.3		85		No	Diagonal	1185	1.94	2302	Leg/Pile	1054	Compression		50	
P23	P23-NF-01	KARMA	1958^{E}	Gulf of Mexico		37	36	4			SD	SD,X,K2		No				132-141	18			52'x90'		1	8.2	31	26	11.5	1	3	50		No	Broadside	1793	1.99	3568						
P23	P23-NF-01	KARMA	1958^{E}	Gulf of Mexico		37	36	4			SD	SD,X,K2		No				132-141	18			52'x90'		1	8.2	31							No	Diagonal	1349	1.54	2083						
P23	P23-NF-01	KARMA	1958^{E}	Gulf of Mexico		37	36	4			SD	SD,X,K2		No				132-141	18			52'x90'		1	8.2	31							No	EndOn	2043	1.47	3007						

NA - Not Applicable
SD - Sub-cellar Deck
CD - Cellar Deck
MD - Main Deck

3.0 RULES OF DEVELOPMENT

3.1 BACKGROUND

With the increasing emphasis on the nonlinear behavior of platforms, it is important to understand the factors influencing their behavior and ultimate strength. In this study, the primary factors affecting platform strength were the number of legs, vertical bracing scheme, vintage, pile grouting, wave in deck, and conductors. Other factors having some effect on platform behavior include overlap of K-joint in K-braced frames, batter of the frames, and effects of plan bracing configurations.

3.2 FACTORS AFFECTING THE RSR

3.2.1 Number of legs

Six- and eight-leg platforms are known to be more redundant than three- and four-leg platforms. The number of legs and type of bracing system can be strong indicators of the overall redundancy and damage tolerance of a platform. In this study the platforms have been grouped into:

- < 4 leg platforms
- 4 leg platforms
- 6 leg platforms
- 8 leg platforms
- >8 leg platforms (8 leg platforms interconnected to two 3 leg auxiliary platforms were also included in this group).

3.2.2 Bracing system

The reserve strength of a platform depends upon the nonlinear behavior of components and the interaction between the components. X-braced platforms are known to be more damage tolerant than K-braced and diagonally braced platforms. In an X-braced frame, after the compression brace buckles, the frame can still carry an additional load through the tension brace. However, the degree of reserve strength depends on the slenderness of the braces and the redundancy throughout the structure, as described in Section 4.

An operator can take advantage of the robustness of an X-braced platform in developing an underwater inspection strategy [2]. This might include extending the interval of periodic underwater inspections. In addition, should significant damage be found during the underwater inspection, the operator might be able to demonstrate that immediate repair is not necessary due to the availability of alternate load paths. Such an approach would allow time for engineering assessment, planning, and evaluation of alternatives.

In the case of K-braced frames, if failure occurs in a K-brace, the load path through the panel is lost and the response is brittle. If the braces are designed to the same codes, the reserve strength of the K-panel will be equal to the safety factor adopted, whereas for the X panel, it may be greater due to the tension brace contribution. This will be demonstrated further in Section 4 for the 2-D frame analysis and is also observed in Section 5 in the dataset analysis.

For diagonal-braced frames, if the compression brace buckles, the frame action in the bay will be lost. If the brace were in tension, and the brace were to yield, frame action is not lost and failure would be more gradual, since tension failures are ductile. A further demonstration of this is also provided in Section 4.

API RP 2A [1] provides guidelines for the ductility requirements in seismically active areas. Although these guidelines were developed for earthquake loading, they can also be used in assessing the redundancy of a structure and the availability of alternative load paths in general. The guidelines include:

- The provision of sufficient system redundancy such that the load redistribution and inelastic deformation will occur before collapse therefore minimizing the abrupt changes in the lateral stiffness of the structure. This provides for a ductile vs. catastrophic brittle failure mode.

- Configure members in vertical frames to provide for redistribution of the horizontal shear loads as buckling occurs in the diagonal bracing and to improve the post-buckling behavior of the diagonal braces. This effectively allows the platform to absorb energy from the earthquake (via member failure) and therefore “survive” an extreme event earthquake, although the platform may be damaged. Again the intent is for the designer to build a ductile failure mode into the system.

3.2.3 Vintage

Over the years, design loads used for the platform design have changed. The platforms in the dataset were grouped based on an internal study by EQE International into the following categories, generally based upon step changes in API RP 2A guidelines. The API chronology was chosen as a basis for the categories since a majority of the platforms in the dataset were designed to API standards.

- *Platforms designed after 1994.* Platforms installed during this period were designed in accordance with the API 20th Edition. This is used as a benchmark for all other designs in this study.

- *Platforms designed between 1977-1993.* These designs were based on API 9th-19th Editions. The 9th edition (1977) was the first version to provide specific 100-year return period criteria, however, the wave load recipe resulted in wave loads below those of the 20th edition, which is now believed to be the most accurate.

- *Platforms designed between 1970-1977.* These designs were based on early versions of API RP 2A. Although not specified in API RP 2A, designs of this era typically used 100-year return period criteria, but used a wave load recipe that resulted in lower loads. In early years, some platforms likely used the 25-year return period criteria.

- *Platforms designed between 1965-1969.* There were no API standards at this time. These designs were a combination of 100-year and 25-year return periods. In 1964, Hurricane Hilda damaged numerous platforms and raised concern over the use of 25-year return period criteria.

- *Platforms designed before 1964.* These designs were typically based on a 25-year or less return period.

The Flooded Member Detection (FMD) JIP by EQE [17] presented data that demonstrates that the occurrence of damage to North Sea platforms increased from 1966 to 1981. This increase in damage was due to the application of design practices for shallow water structures in 60’s and 70’s to the deeper water structures of the mid to late 70’s. Improved design methods, greater understanding of fatigue, improved fabrication and inspection standards, improved steel quality and improved operating procedures have since reduced the damages. This reduction becomes evident in those platforms installed after 1985.

PMB [4, 6], while studying the effects of Hurricane Andrew on offshore platforms found that a majority of the severely damaged or failed platforms were of 1960's or earlier vintage. No platforms designed to API RP 2A 9th edition (1977) or later were found to have sustained damage or fail during Hurricane Andrew.

3.2.4 Pile grouting

Grouting of the leg/pile annulus is known to improve the strength of members and joints, thereby contributing to the increase in capacity of the platform [9]. Additionally, grouting will increase the rotational restraint imposed by the joint and, thereby, increase the buckling capacity of the connected member(s) [11].

3.2.5 Wave in deck

A number of older platforms are designed for wave heights that are relatively low by current standards. In some cases, these platforms have deck elevations low enough for the platform to experience waves impacting the deck in a large storm or hurricane. This was the lesson learned by operators in the Gulf of Mexico during the 1960's who used a 25-year return period design wave instead of the 100-year return period wave used today.

If the wave crest inundates the deck, there will be a dramatic increase in platform loading due to the increased hydrodynamic area of equipment and the deck itself. When this occurs, the elevation of the centroid of the applied lateral force may be significantly higher than that of a wave that does not inundate the deck. The higher center of force could increase the overturning moment and shift the failure mechanism from a jacket member failure to a deck portal frame or a pile pullout failure [5].

An indication of the wave in deck is measured by air gap, which may be defined as the difference between deck height and the calculated crest of the design wave (100-year). When the air gap is eliminated, a greater area of the platform is exposed and the hydrodynamic loading increases tremendously. In the event of an extreme storm loading, a platform with lower reserve strength and a higher air-gap may have a higher probability of surviving than another structure with a high reserve strength and lower air-gap [8].

3.2.6 Conductors

In most cases, conductors are modeled as load attracting members. Their capability to resist wave loads is sometimes neglected in the original platform design (a conservative practice). For structures with limited foundation resistance, conductors with mudline framing can contribute significantly (up to 10% or more) to the foundation stiffness and collapse strength of the structure.

4.0 PUSHOVER ANALYSIS OF 2-DIMENSIONAL FRAMES

4.1 GENERAL REMARKS

In order to further understand the effect of bracing scheme and damage on the robustness of the platforms and load paths, pushover analyses were performed on two-dimensional frames with five different bracing schemes for the loads shown in Figure 4.1. All were two-bay frames in water depth of 111ft. The SACS suite of programs [3] was used to perform the pushover analyses. The bracing schemes (Figures 4.1 (a) to 4.1(e)) include:

- X-bracing
- K1-bracing (K pointed down)
- K2-bracing (K pointed up)
- Single Diagonal (Compression) bracing
- Single Diagonal (Tension) bracing

This section reports the results of twenty-nine ultimate strength analyses including six pushovers of undamaged frames and twenty-three pushovers in damaged states.

4.2 DESIGN METHODOLOGY USED FOR 2-D FRAMES

The two dimensional frames were designed elastically using the SACS program [3] for the lateral loads of 300 kips and 150 kips located at the top two elevations of the framing. The loads are split between nodes 301, 303 and 201, 203 in order to provide a more accurate representation of distributed wave loads acting on a platform. The total load on the platform is therefore 450 kips. These load values are representative of wave loading for a platform in this water depth [13, 14].

The frames are representative of the platform studied as a part of the API "CBC Analysis Validation" by EQE [13, 14]. The design loads are based on API RP 2A 20th edition. Results of the elastic analyses and member sizes used for the ultimate strength analyses can be found in Appendix A.

For the purposes of this study, overlap of K-joints was assumed in the 2-D model even though this may not hold true in some older platforms. The overlap introduces an element of joint redundancy as the applied load can be partly transferred from one brace to another through their common weld.

The criterion used for member selection was to obtain unity checks for all components as close to unity as possible. While designing the X-braced and K-braced frames, it was found that, the tension braces and horizontals carried negligible loads. Design of these members resulted in smaller diameter and wall thickness (when the unity check was intended to be as close to 1.0 as possible). In practice, however, the compression and tension braces are typically of equal size. Since the compression member design governs the design of vertical braces in a given panel, an alternative design was analyzed in which the member selected for compression was used for tension as well regardless of the resulting unity ratio.

Pushover analyses of these frames show that structural optimization based solely on the linear analysis significantly reduces the reserve strength and the degree of redundancy of the structure, particularly for X-braced frames. A comparison of the pushover analyses of the fully optimized design to the design reflecting common practice for an X-braced frame is shown in Figure 4.2. In Figure 4.2 and subsequent figures, the load factor is the ratio of factor is the applied load to the design lateral load (450 kips). This figure demonstrates the redundancy contributed by the tension braces, when they are same size as the compression brace.

The latter design (equal compression and tension braces) was used for the study of the robustness of the frames.

4.3 UNDAMAGED FRAMES

This section discusses the behavior of the bracing schemes described in section 4.2 in their intact or undamaged conditions. For this study, the reserve strength ratio (RSR) for a frame is defined as the ratio of lateral load at ultimate strength to design lateral load (450 kips). The performances of the bracing schemes are summarized in Table 4.1 and a comparison of the load-displacement curves is shown in Figure 4.3.

- *X-braced Frame*: In X-braced frames, if one of the compression braces fails, the tension braces resist the load, thus allowing the frame to carry a higher load (recall that the compression braces will fail first due to buckling, with the load taken by the tension braces). In the linear analyses, these tension braces and horizontal braces had very low unity checks. However, in pushover analysis, they act in parallel, thus improving the performance of the frame. Maximum RSR is 2.50.

- *K1-braced Frame*: In the K1-braced frame, if the compression brace buckles, the load path through the bracing is lost. Maximum RSR is 2.43.

- *K2-braced Frame*: In the K2-braced frame, once the compression brace 3-203 buckles, the horizontal brace transfers the additional load, thus maintaining the frame action. The load-deflection curve in Figure 4.3 shows that the frame carries load beyond the buckling of compression braces and reaches a maximum RSR of 2.29.

- *Single diagonal (compression)-braced Frame (SD1)*: In the single diagonal brace-frame, where the braces are in compression, once the compression brace buckles, the frame action is lost. The maximum RSR is 2.38.

- *Single diagonal (tension)-braced Frame (SD2)*: For the single diagonal-braced frame loaded in tension, once the tension brace yields, the load path is not lost and the failure is more gradual. The maximum RSR is 1.99.

4.4 DAMAGED FRAMES

The discussion in Section 4.3 shows how different framing configurations affect the availability of alternative load paths in the system. To understand the robustness of the bracing schemes, and in order to provide information for inspection planning, it is important to understand the behavior of the damaged frames. This section describes the behavior of the frames in different damaged configurations. The damage being considered here is the complete loss of a member, as by brittle fracture, fatigue failure, or collision damage.

In order to study the behavior of damaged frames, the frames were pushed over with one member removed at a time. The sequence of removing the members is shown in Figures 4.4(a)-4.4 (b). The following factors were used to quantify the comparison of the damaged and intact platforms.

Residual strength is defined as the ability of a damaged structure to sustain loads in excess of the design value [2]. Residual strength is measured by the Damage Strength Ratio (DSR) as:

$$\text{DSR} \quad \frac{\text{Lateral load at Collapse (damaged)}}{\text{Design lateral load}}$$

The performance of a damaged platform in comparison to the intact platform can be measured by the Residual Resistance Factor (RRF). The Residual Resistance Factor is defined as the ratio of lateral load at collapse in the damaged state, to the lateral load at collapse in the undamaged state of the structure [2].

$$\text{RRF} \quad \genfrac{}{}{0pt}{}{\text{Lateral load at Collapse (damaged)}}{\text{Lateral load at Collapse (undamaged)}}$$

The load-displacement curves for the damaged cases are shown in Figures 4.5-4.9 for X-, K1-, K2-, SD1-, and SD2-braced frames, respectively. The load displacement curves for the intact frames are also shown for reference. These cases are discussed as follows:

- *X-braced Frame:* Five damaged cases were analyzed. Figure 4.5 shows the resulting load-deflection curves. Table 4.2, which summarizes the DSRs of the damaged cases, shows that Case 3 has damage to the upper bay tension brace results in the least capacity. Once the upper compression brace (1) buckles, there is no load path through the upper bay and, thus, the frame fails. Case 5, damage to the horizontal brace results in the least reduction in capacity. Based on the analyses, the most important member (in terms of producing the lowest DSR) is the upper tension brace in Case 3.

- *K1-braced Frame:* Six damaged cases were run for the K1-braced frame, the results of which are summarized in Table 4.2. The load-deflection curves of the damaged scenarios are shown in Figure 4.6. Case1, removal of the tension brace in the upper bay is the critical case for this bracing scheme, once the compression brace buckles, failure occurs abruptly. Case 3, damage to the upstream horizontal brace results in the least reduction in capacity. The most important member is the upper bay tension results in Case 1.

- *K2-braced Frames:* Six damaged cases were run for the K2-braced frame. The results of the analyses are summarized in Table 4.2. Figure 4.7 shows the load-deflection curves for the six damaged scenarios. The most important members are the tension and compression braces in Cases 1 and 2. Case 3, damage to the upstream horizontal results in the least reduction in capacity.

- *Single diagonal (compression)-braced Frame (SD1)*: Three damaged cases were run for the single diagonal (compression)-braced frame. Table 4.2 summarizes the DSRs of the damaged cases. The load deflection curves of the damaged frames are shown in Figure 4.8. The most important member is the compression brace in upper bay in Case 1.

- *Single diagonal (tension)-braced Frame (SD2):* Three damaged cases were run for the single diagonal (tension)-braced frame. Results are summarized in Table 4.2. Figure 4.9 shows the plot of load-deflection curves of the damaged scenarios. The most important member is the upper tension brace in Case 1.

A comparison of minimum, mean, and maximum damage strength ratios (DSR) for X-, K1-, K2-, and single diagonal (compression)- (SD1), and single diagonal (tension)- (SD2) bracing schemes is shown in Figure 4.10. The mean DSR of a particular frame is the mean of the damage strength ratios of the frame. Figure 4.10 shows that the X-braced frames are more damage tolerant than the other types of bracing schemes.

Figure 4.11 summarizes the most important and least important members for the five frames studied. The most important member is the member that if damaged will result in the largest decrease in platform capacity. The least important is the member that it damaged will result in lowest decrease in platform capacity.The figure demonstrates the importance of tension braces in terms of "robustness" in X, K1, K2 frames. Once the compression brace buckles, the load path through the bay is lost and the frame collapses.

While the study of the two-dimensional frames, provides a good understanding on the robustness of frames, there are other factors, which effect the member importance, including the sizing of members, out of plane bracing (3-D frames), torsion effects, etc.

As mentioned before, the frames were "optimally" designed for wave load only. In reality, the proportioning may not be so exact since some of the members may get even bigger once the jacket is checked for loadout, launch, transport, lifting and other loads. Another consideration would be that the waterline members typically have some increase in wall thickness corrosion allowance. These factors if considered might change the sizes of members used and hence the pushover results.

To demonstrate this, the X-brace frame was designed such that the upper bay vertical diagonals have the same sizes as those of the lower bay . Figure 4.12 shows the load displacement curves of the modified X-braced frame in the damaged and undamaged states. Case 4 has damage to the lower bay tension brace results in the least capacity. Once the lower compression brace (2) buckles, there is no load path through the lower bay and, thus, the frame fails. Case 5, damage to the horizontal brace, results in the least reduction in capacity. Based on the analyses, the most important member (in terms of producing the lowest DSR) is the upper tension brace in Case 4.

Figure 4.13 compares the member importance of the two X-braced frames used. While Figure 4.13 (a) shows the member importance for the X-braced frame used in Figure 4.5, Figure 4.13 (b) shows the member importance used in Figure 4.12. The most important member in the original frame is the upper bay tension brace while the most important member for the modified frame is the lower bay tension brace.Another factor that effects the member importance in a frame is the out-of-plane bracing. Results of a study by EQE [20, ****Simon take care of the reference***] are presented in Appendix B to demonstrate the effect of out-of-plane bracing, where the out of plane bracing changes the priority of members from upper vertical diagonals in the two-dimensional case to the lower bay members.

4.5 ROBUSTNESS OF THE FRAMES

Robustness is the measure of a structure's ability to sustain damage with a limited loss of reliability, i.e., the more damage tolerant the frame is, the more robust is the frame. The larger the Residual Resistance Factor (RRF), the more robust (damage tolerant) the platform. For any particular platform, as more and more members are damaged, the reserve strength of the platform, as measured by DSR, decreases. Robust structures experience a lesser decrease in the reserve strength of the damaged platform as compared to others.
The RRFs for the damaged cases described in Section 4.4 are summarized in Table 4.3. Figure 4.12 shows the comparison of minimum, mean, and maximum RRFs for the bracing schemes under study.

Table 4.3 Performance (RRF) of damaged frames

Damage Case	Residual Resistance Factor (RRF)				
	X	**K1**	**K2**	**SD1**	**SD2**
Case 1	0.80	0.18	0.17	0.16	0.17
Case 2	0.83	0.18	0.17	0.35	0.37
Case 3	0.48	0.62	0.70	0.51	0.54
Case 4	0.56	0.58	0.55		
Case 5	0.97	0.58	0.53		
Case 6		0.56	0.55		

$$\mathrm{RSR} \quad \frac{\text{Lateral load at ultimate strength of the platform}}{\text{Design lateral load}}$$

$$\mathrm{DSR} \quad \frac{\text{Lateral load at Collapse (damaged)}}{\text{Design lateral load}}$$

$$\mathrm{RRF} \quad \frac{\text{Lateral load at Collapse (damaged)}}{\text{Lateral load at Collapse (undamaged)}}$$

Overall, the X-bracing scheme is the most robust design followed by the K-bracing schemes. In practice, many offshore platforms have diagonal bracing with braces in tension or compression for different horizontal parallel bays (see Figure 4.13), which can be more effective than the K-bracing scheme.

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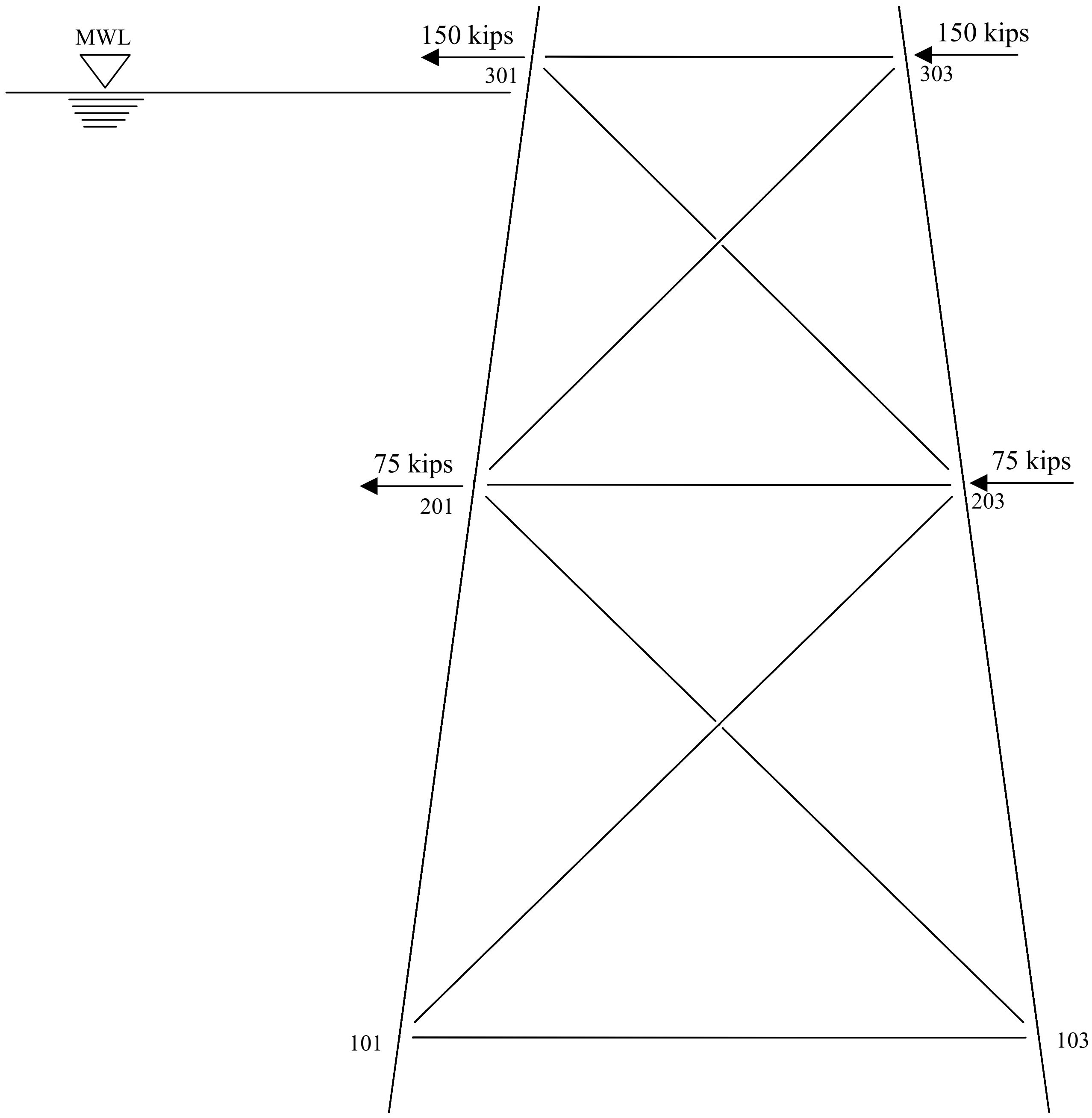


Figure 4.1 (a) X-braced frame

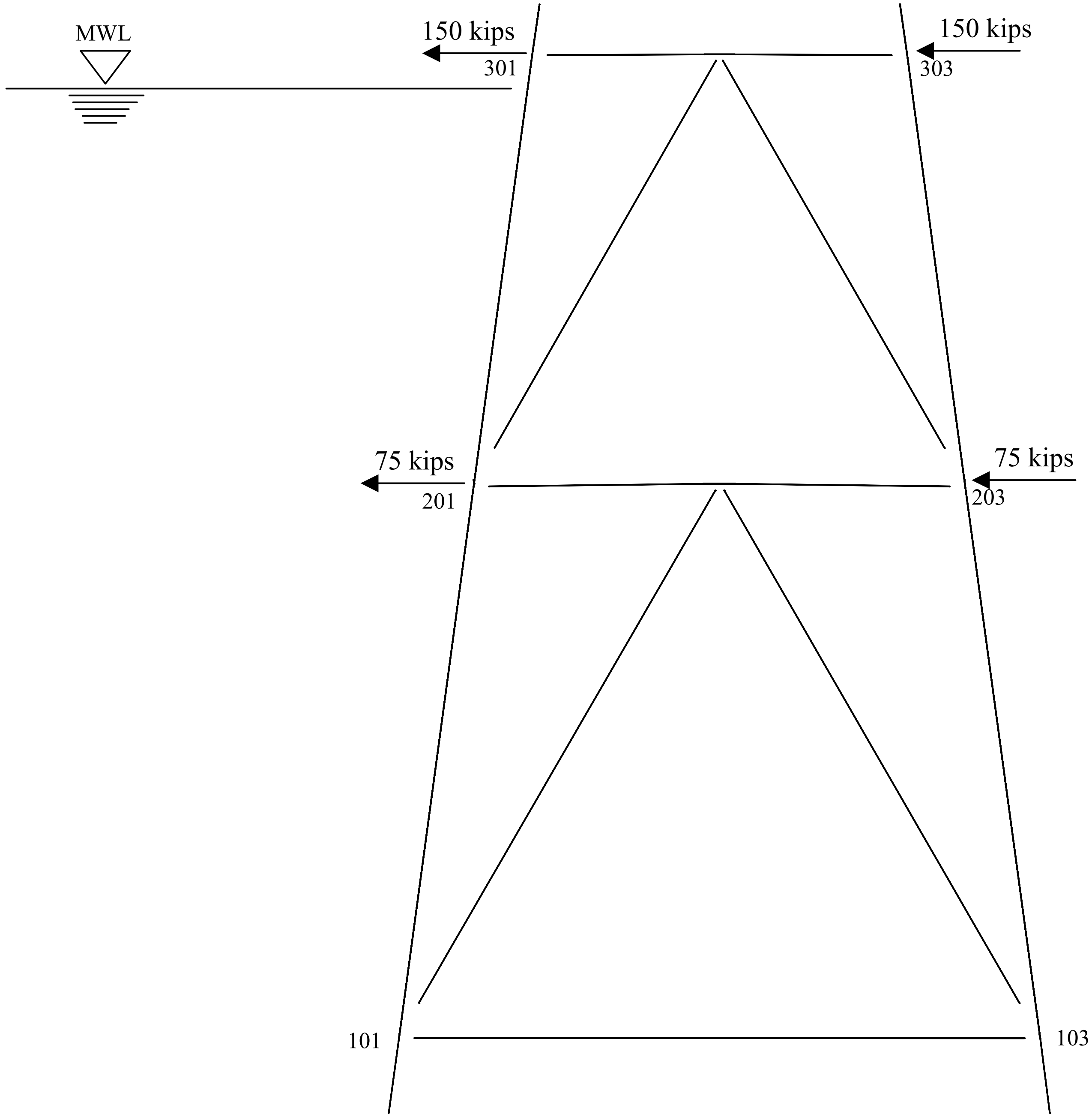


Figure 4.1 (b) K1-braced frame

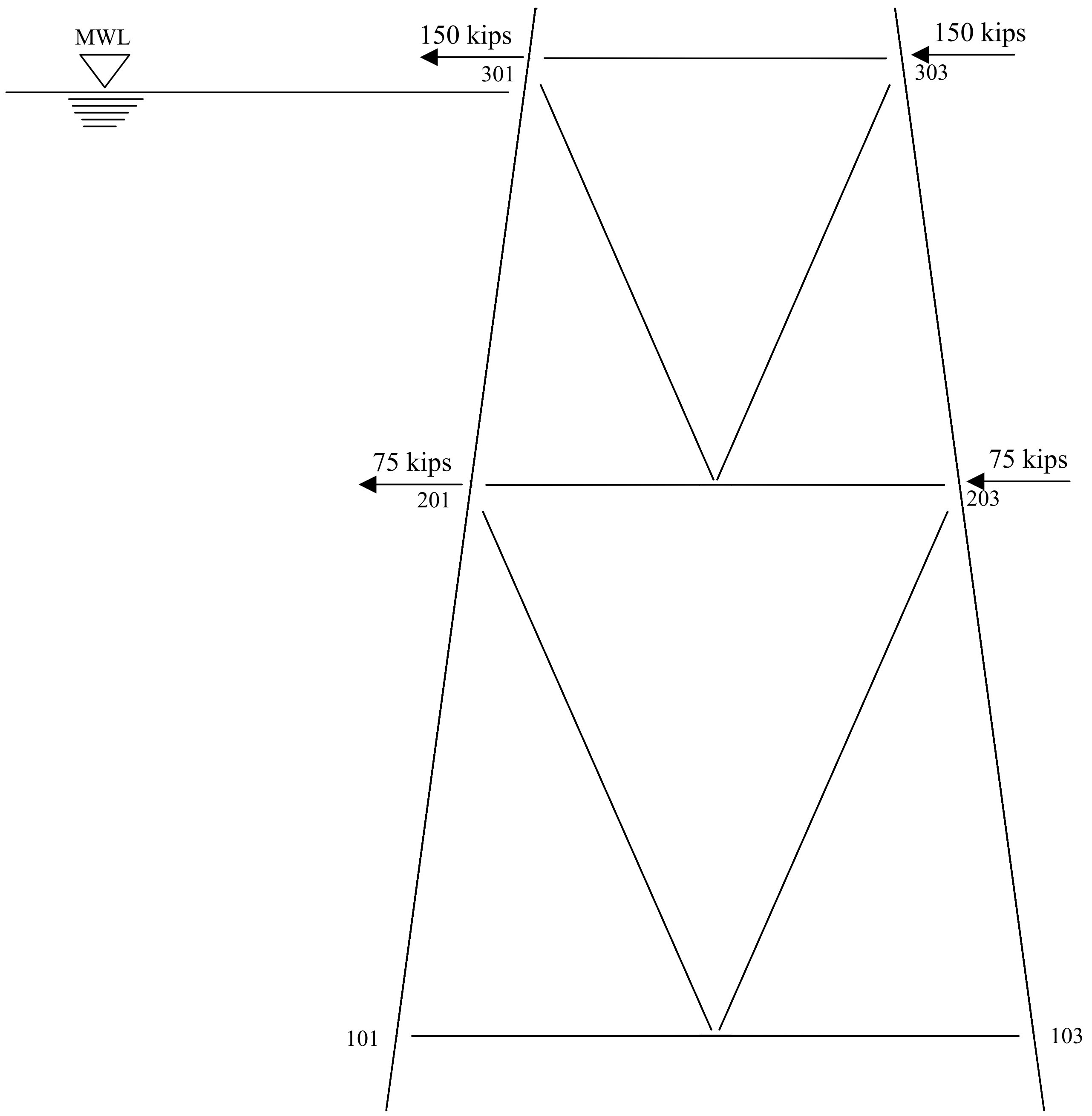


Figure 4.1 (c) K2-braced frame

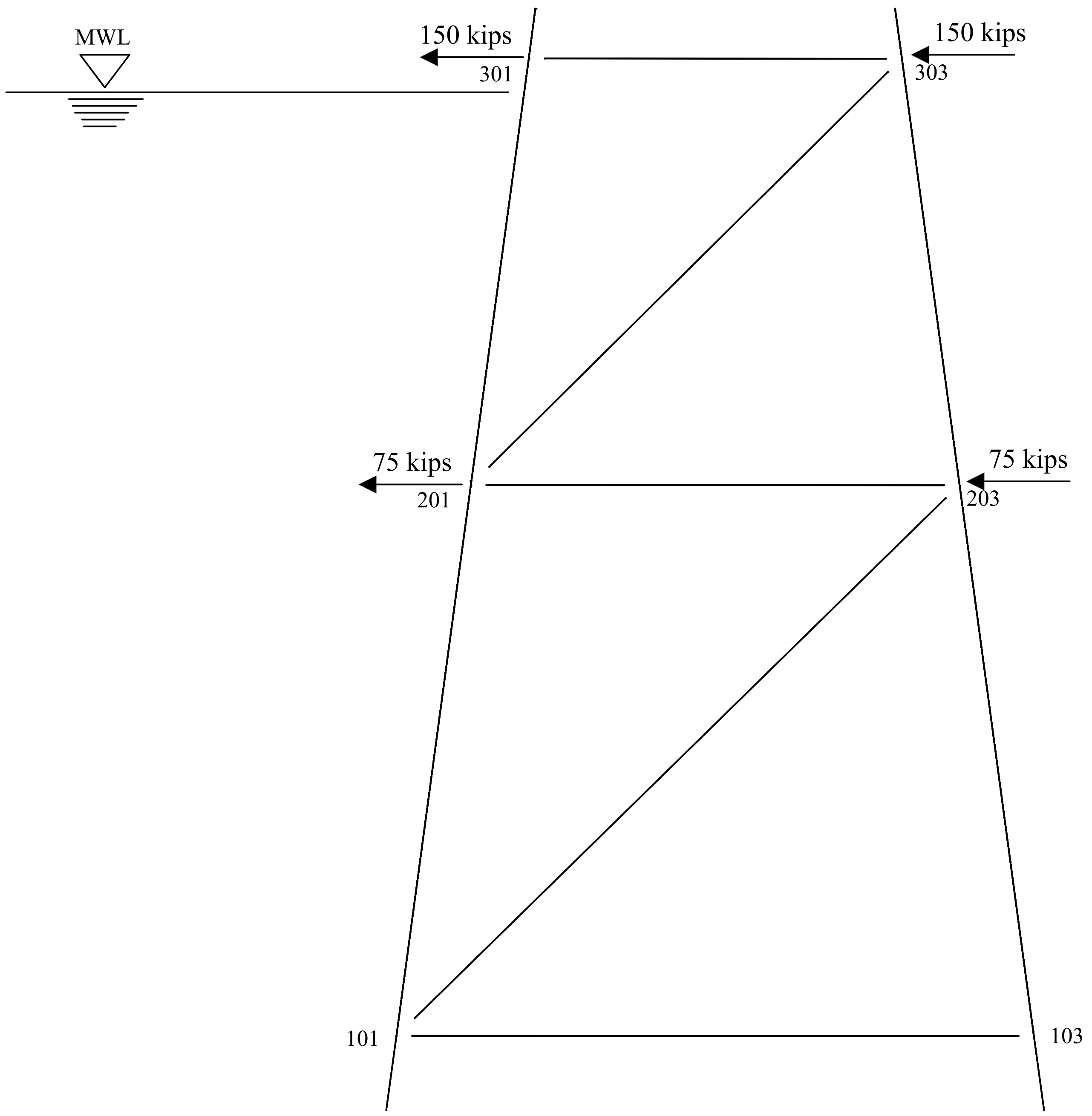


Figure 4.1 (d) Single diagonal (compression) braced frame

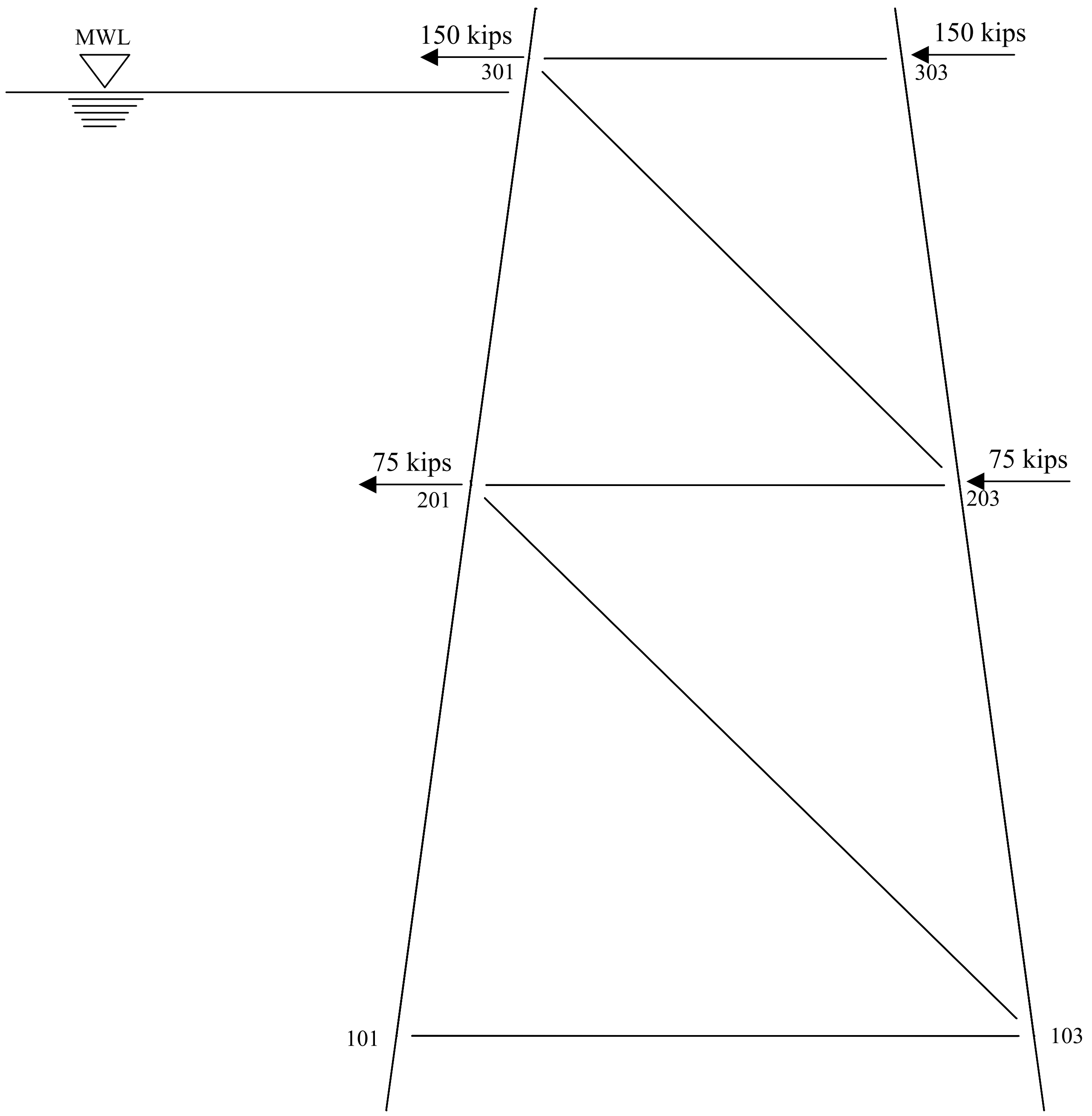


Figure 4.1 (e) Single diagonal (tension)-braced frame

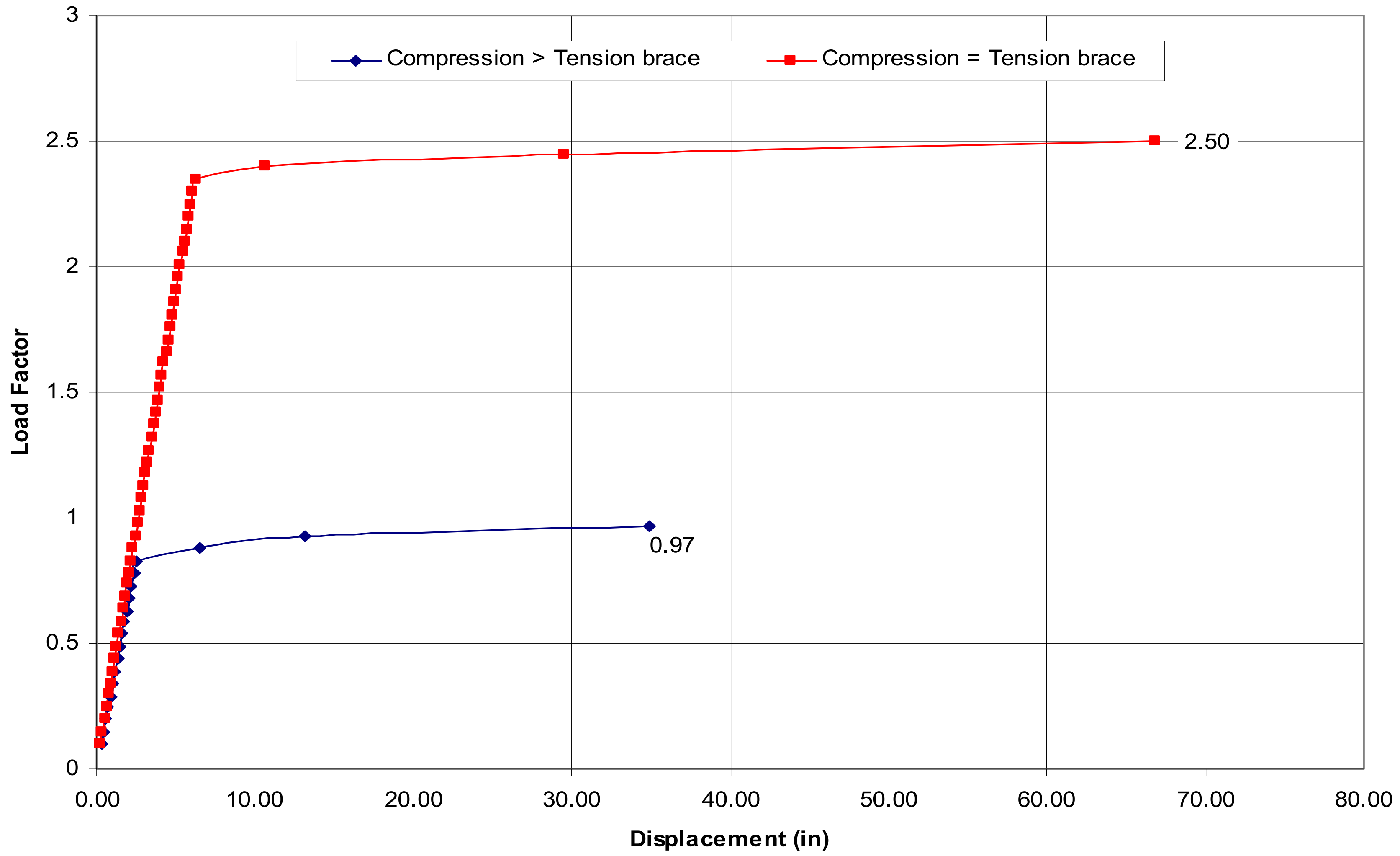


Figure 4.2 Load deflection curves for different designs of X-braced frames

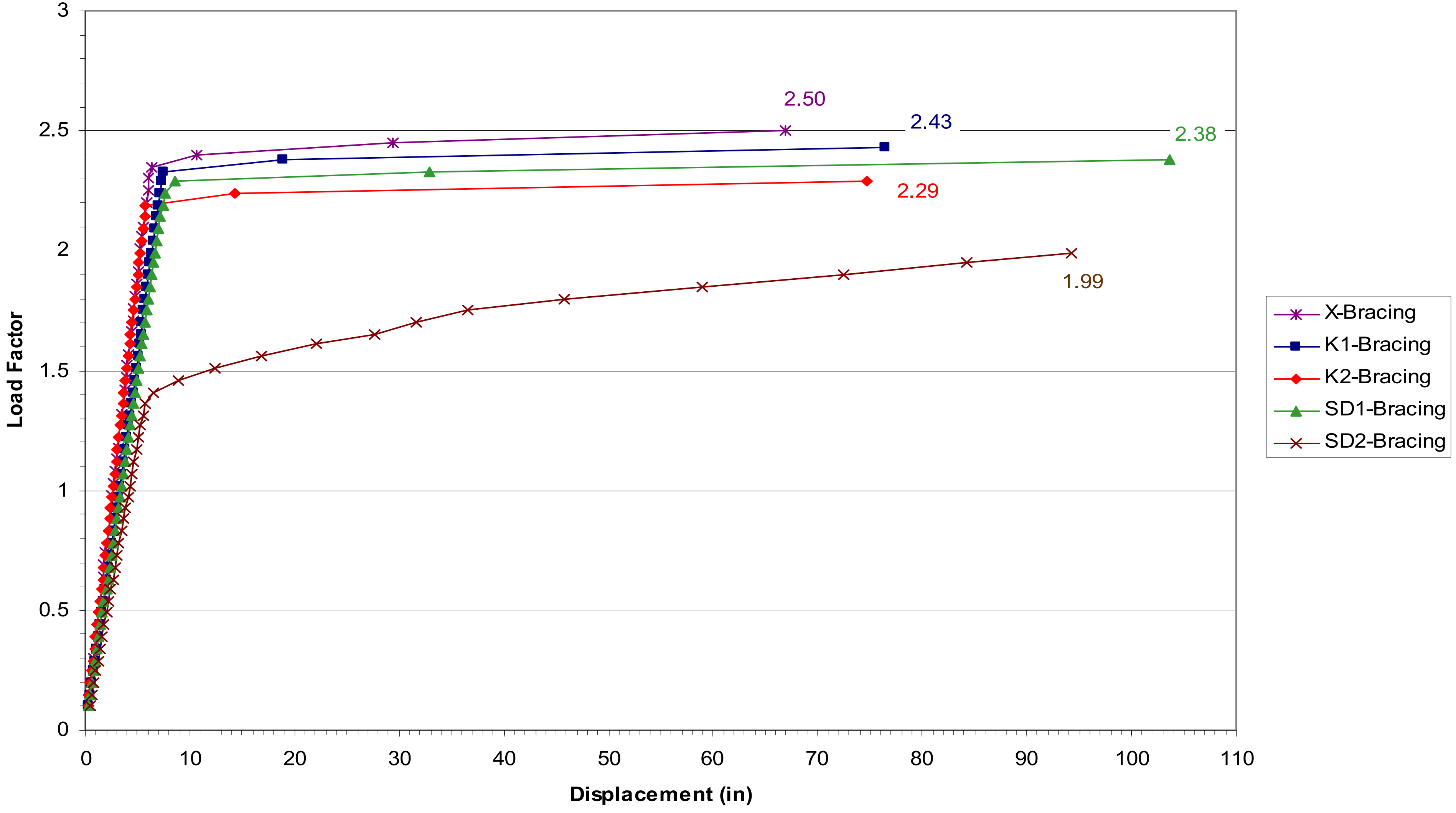


Figure 4.3 Load deflection curves for intact frames

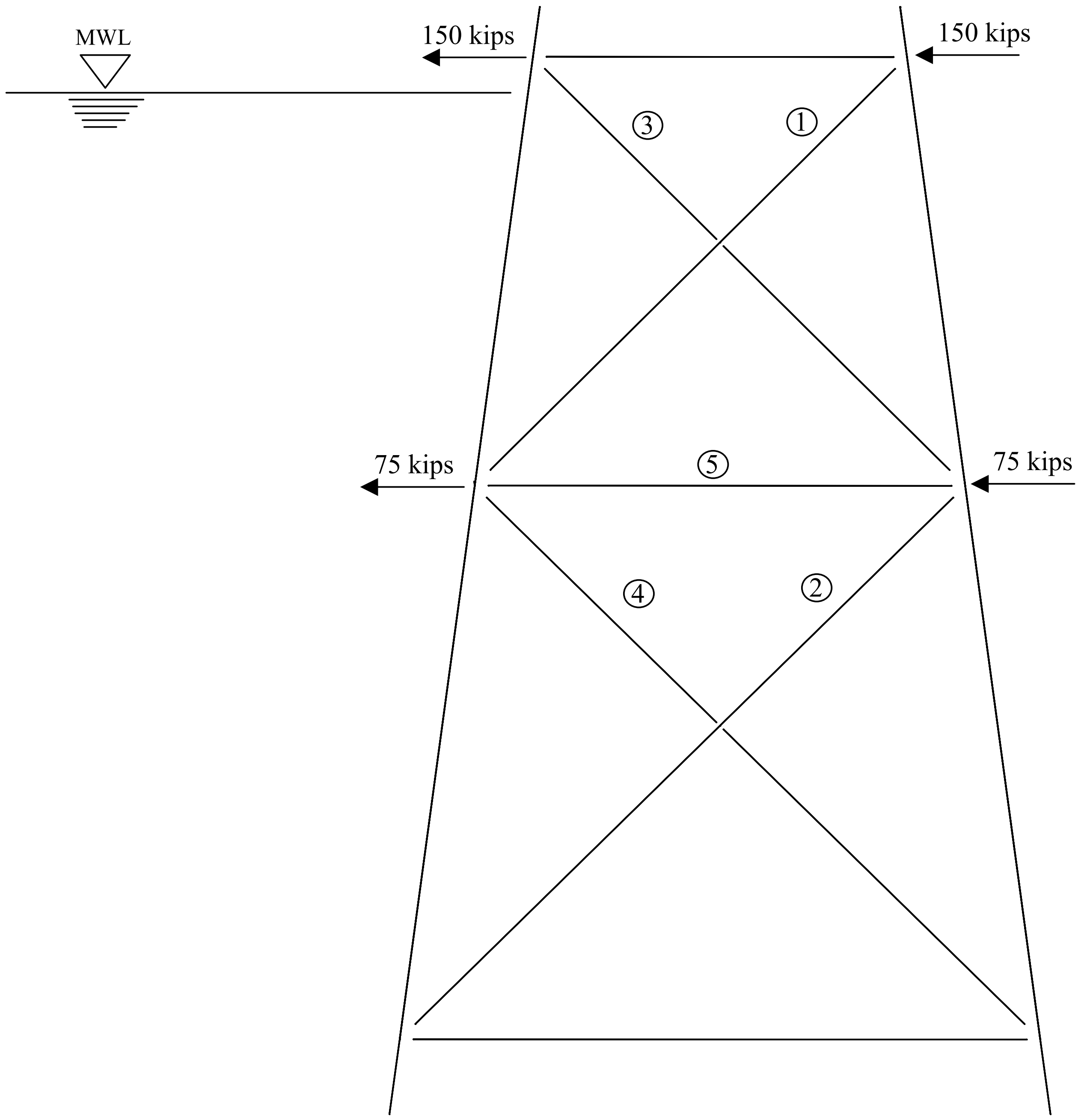


Figure 4.4 (a) Damaged cases of X-braced frame (one member removed at a time)

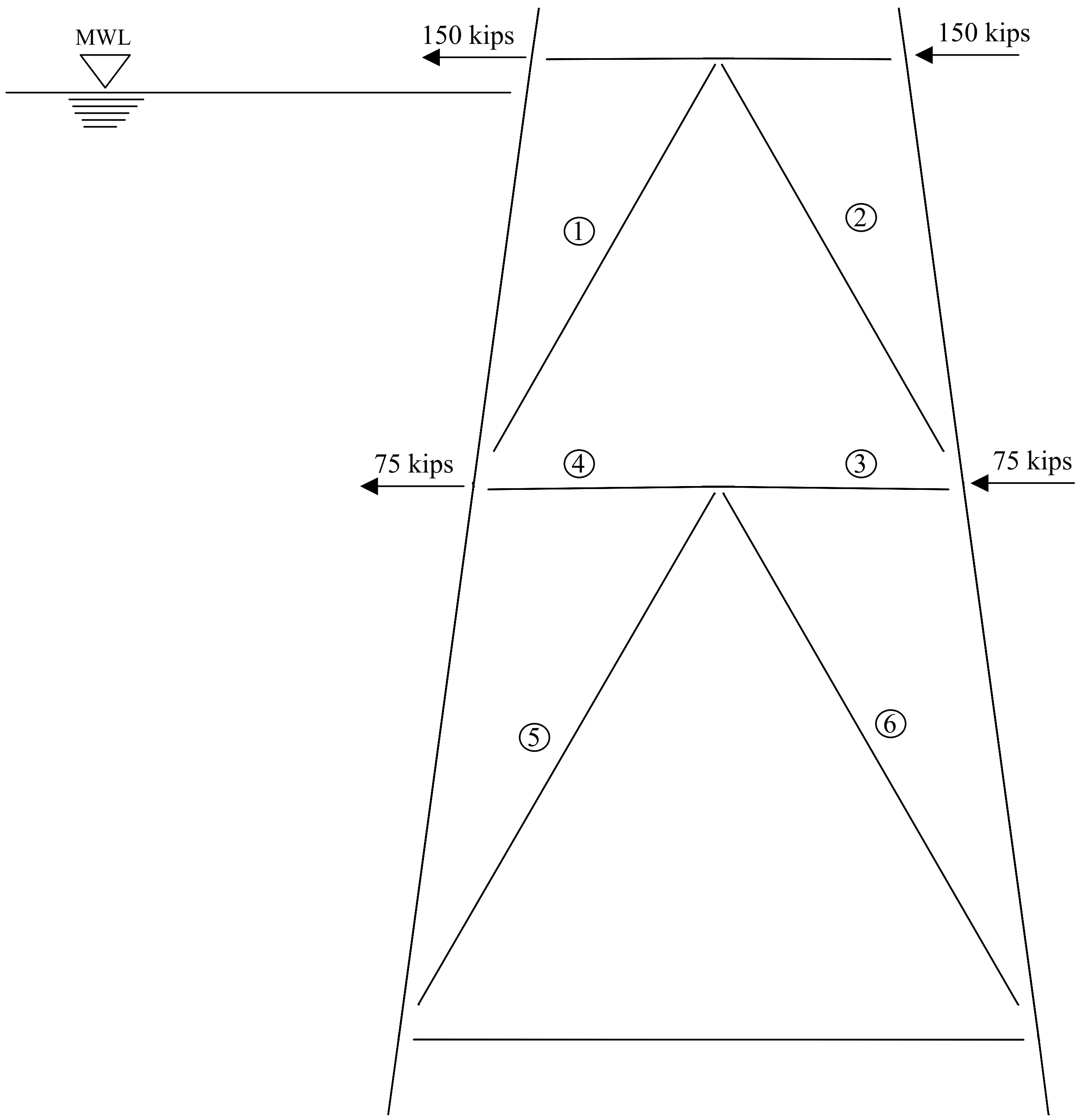


Figure 4.4 (b) Damaged cases of K1-braced frame (one member removed at a time)

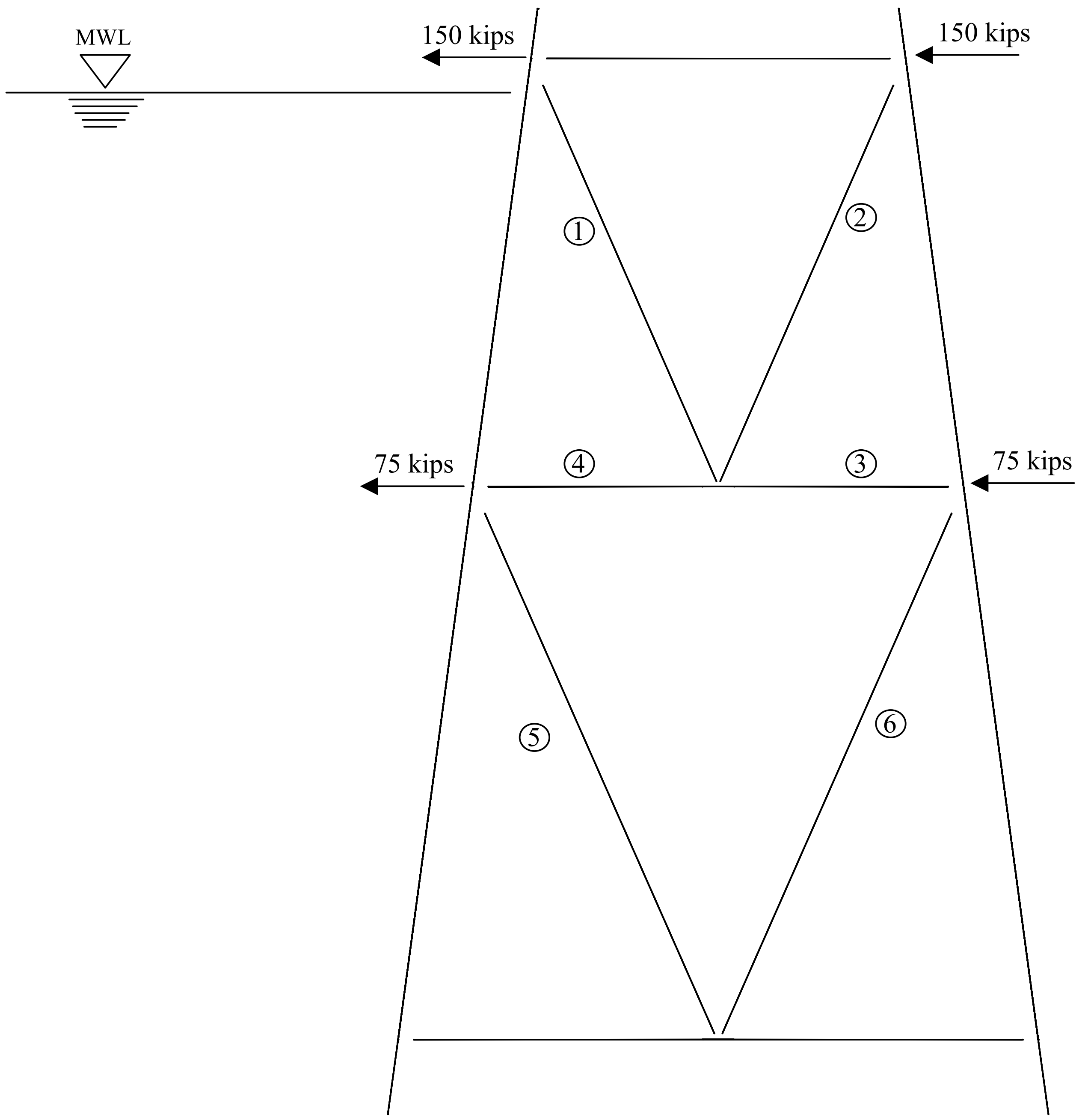


Figure 4.4 (c) Damaged cases of K2-braced frame (one member removed at a time)

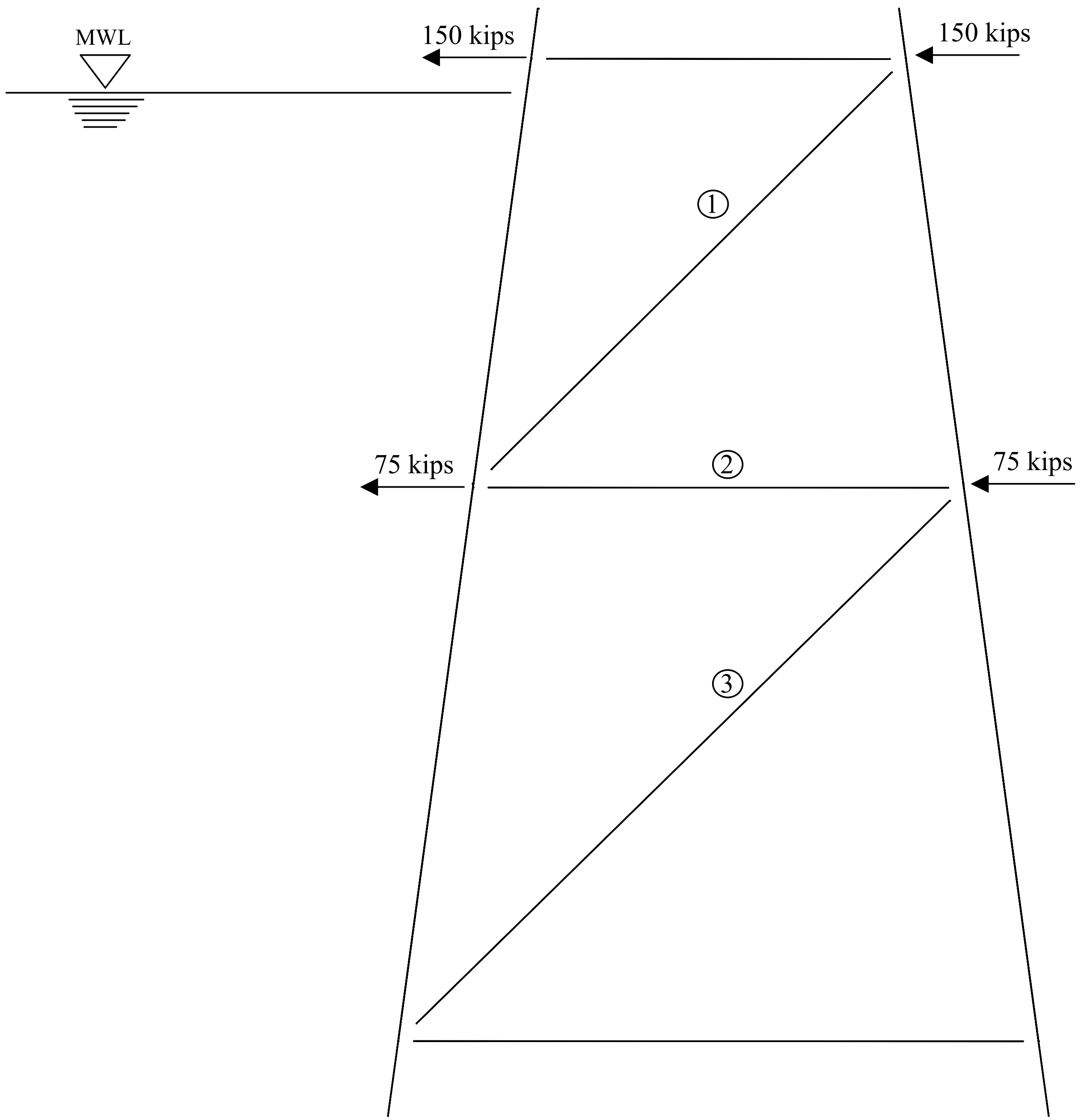


Figure 4.4 (d) Damaged cases of single diagonal (compression)-braced frame (one member removed at a time)

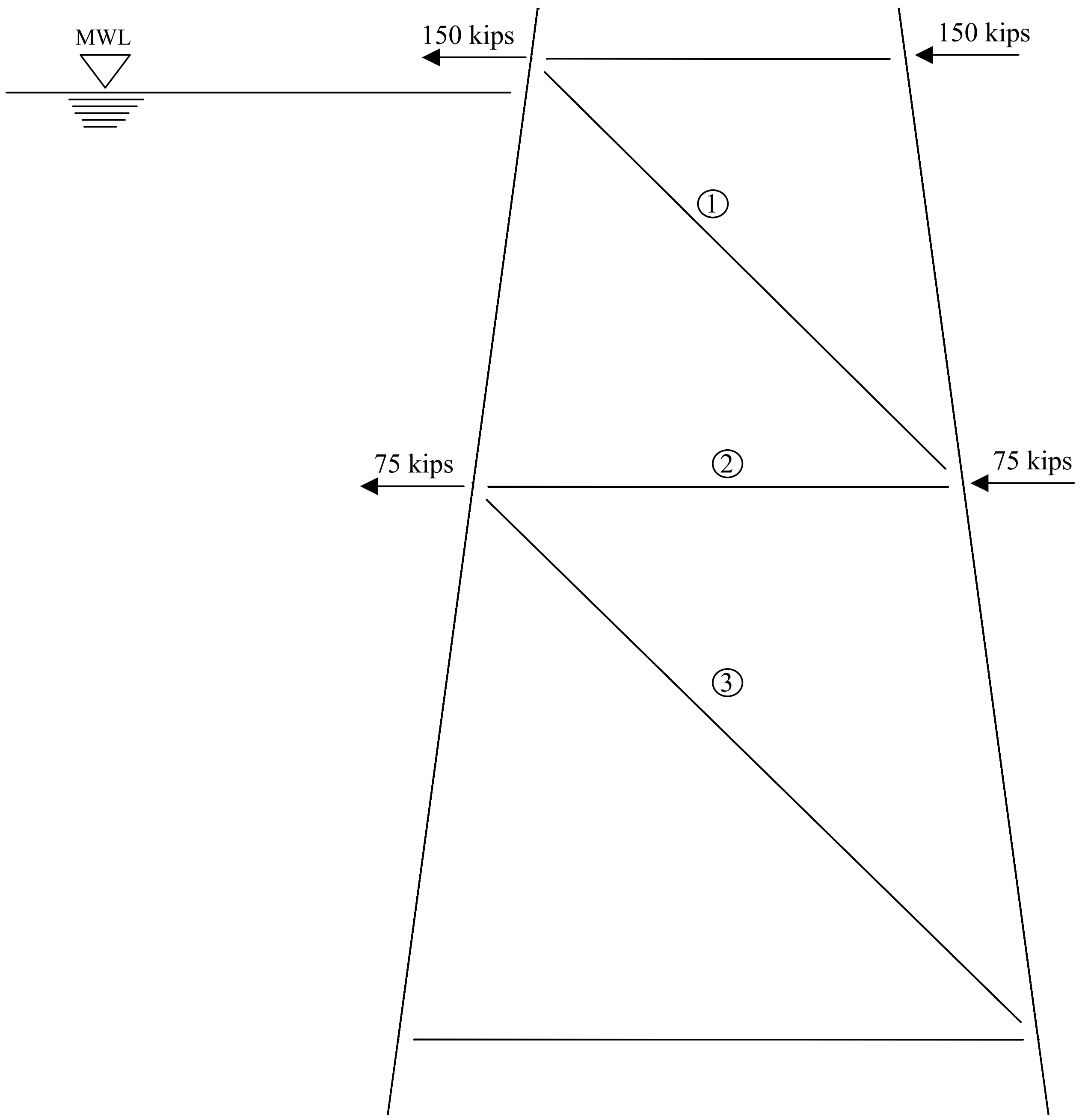


Figure 4.4 (e) Damaged cases of single diagonal (tension)-braced frame (one member removed at a time)

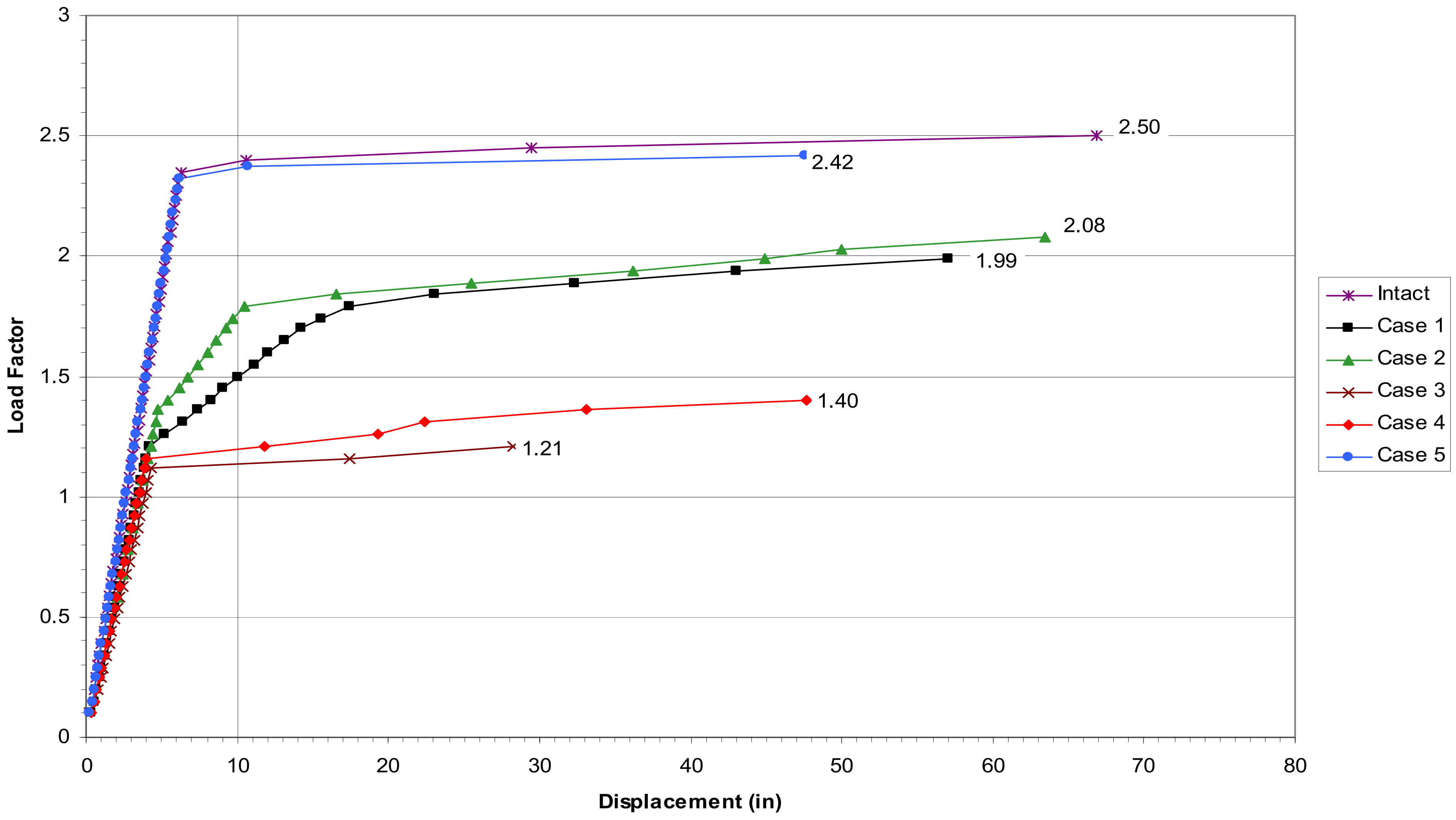


Figure 4.5 Load deflection curves for damaged X-braced frames

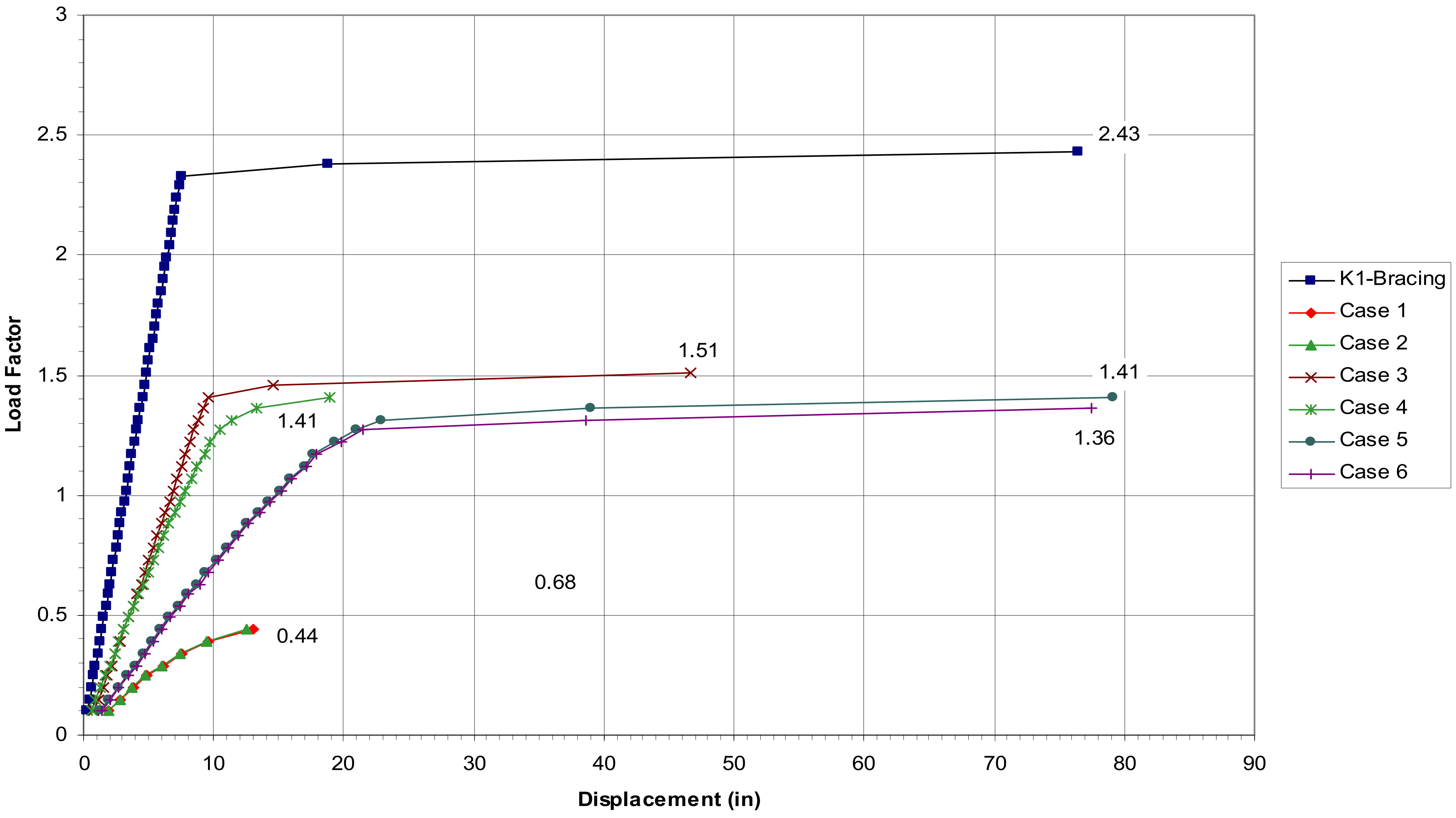


Figure 4.6 Load deflection curves for damaged K1-braced frames

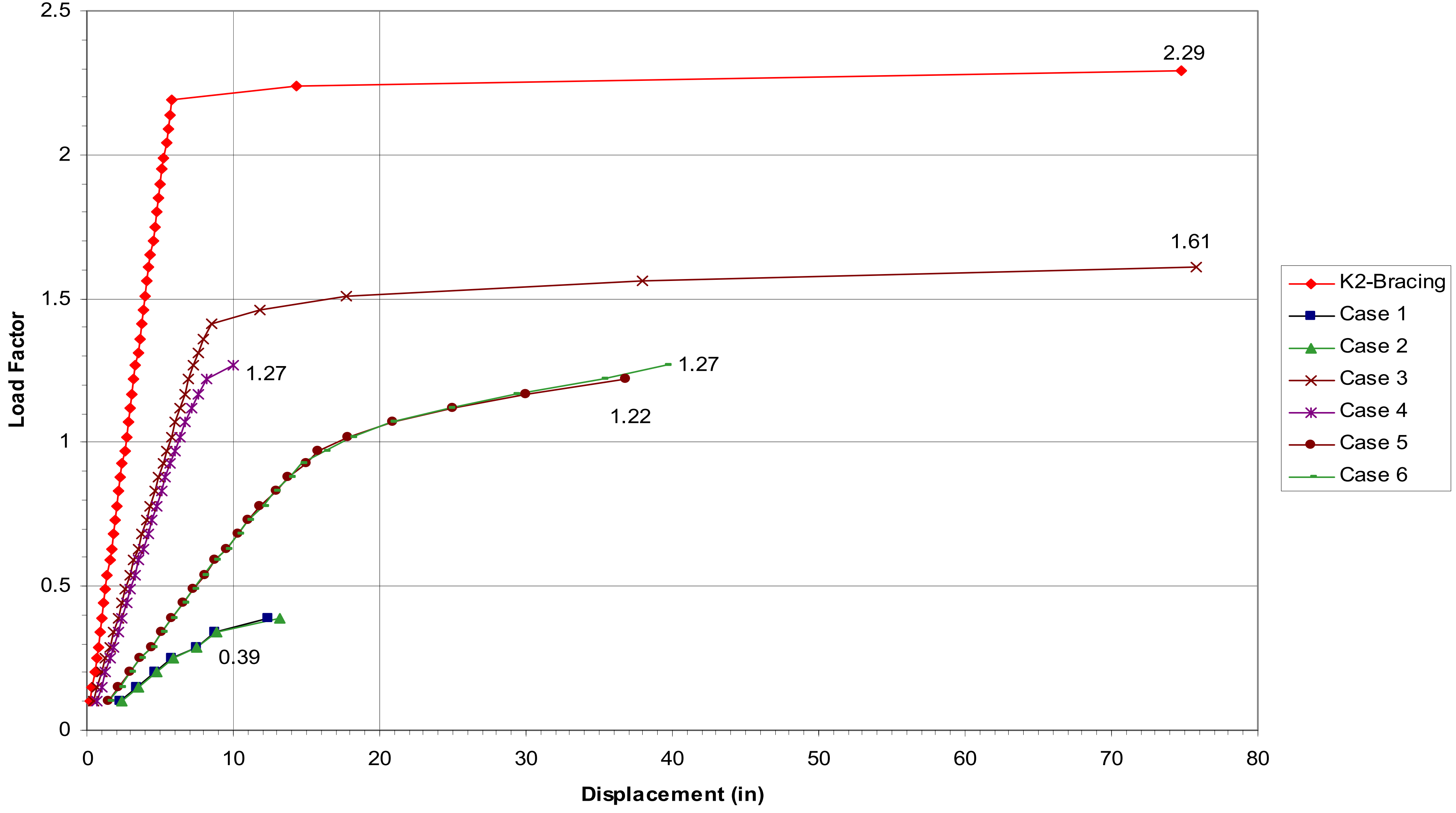


Figure 4.7 Load deflection curves for damaged K2-braced frames

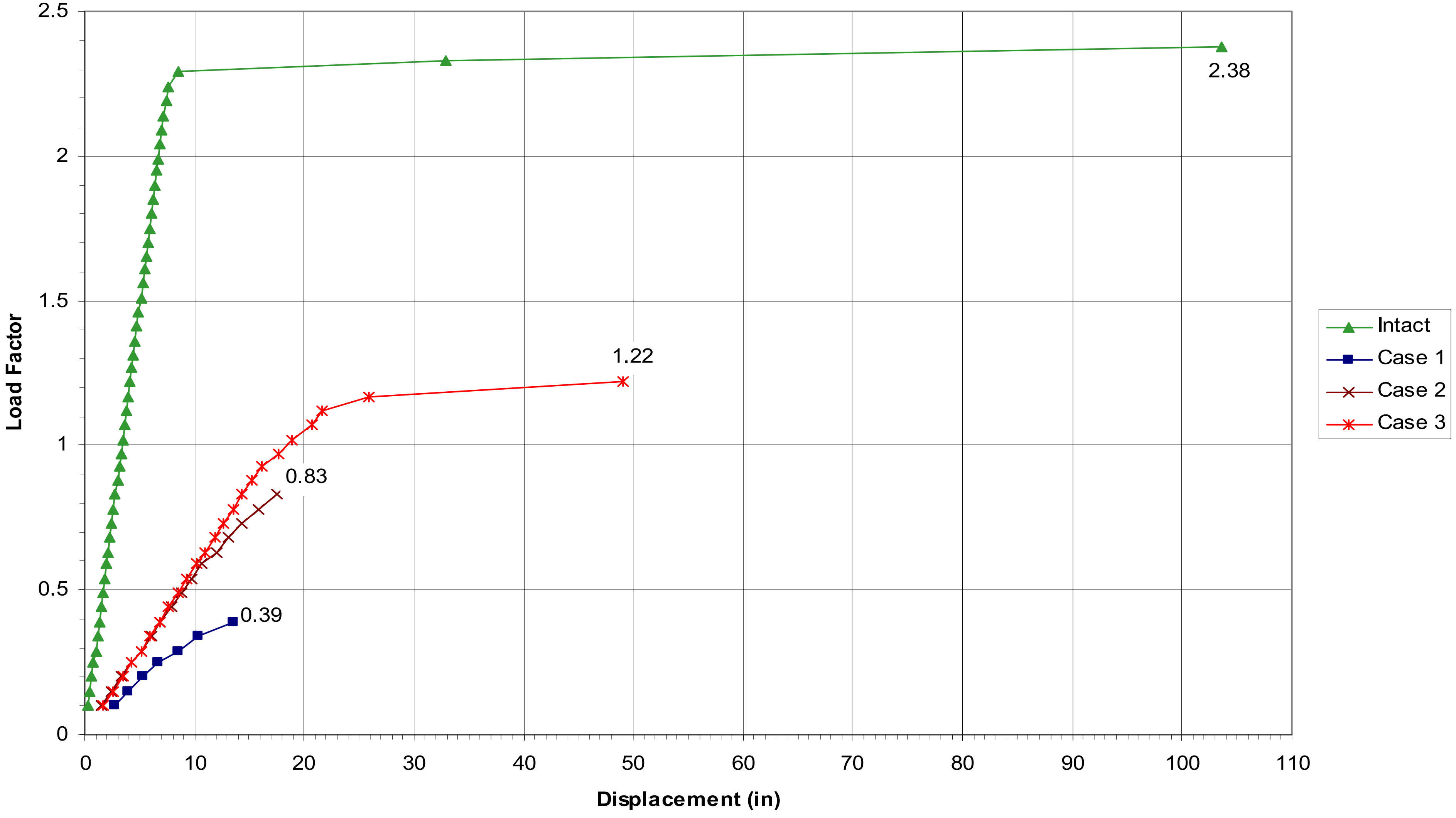


Figure 4.8 Load deflection curves for damaged single diagonal (compression) braced frames

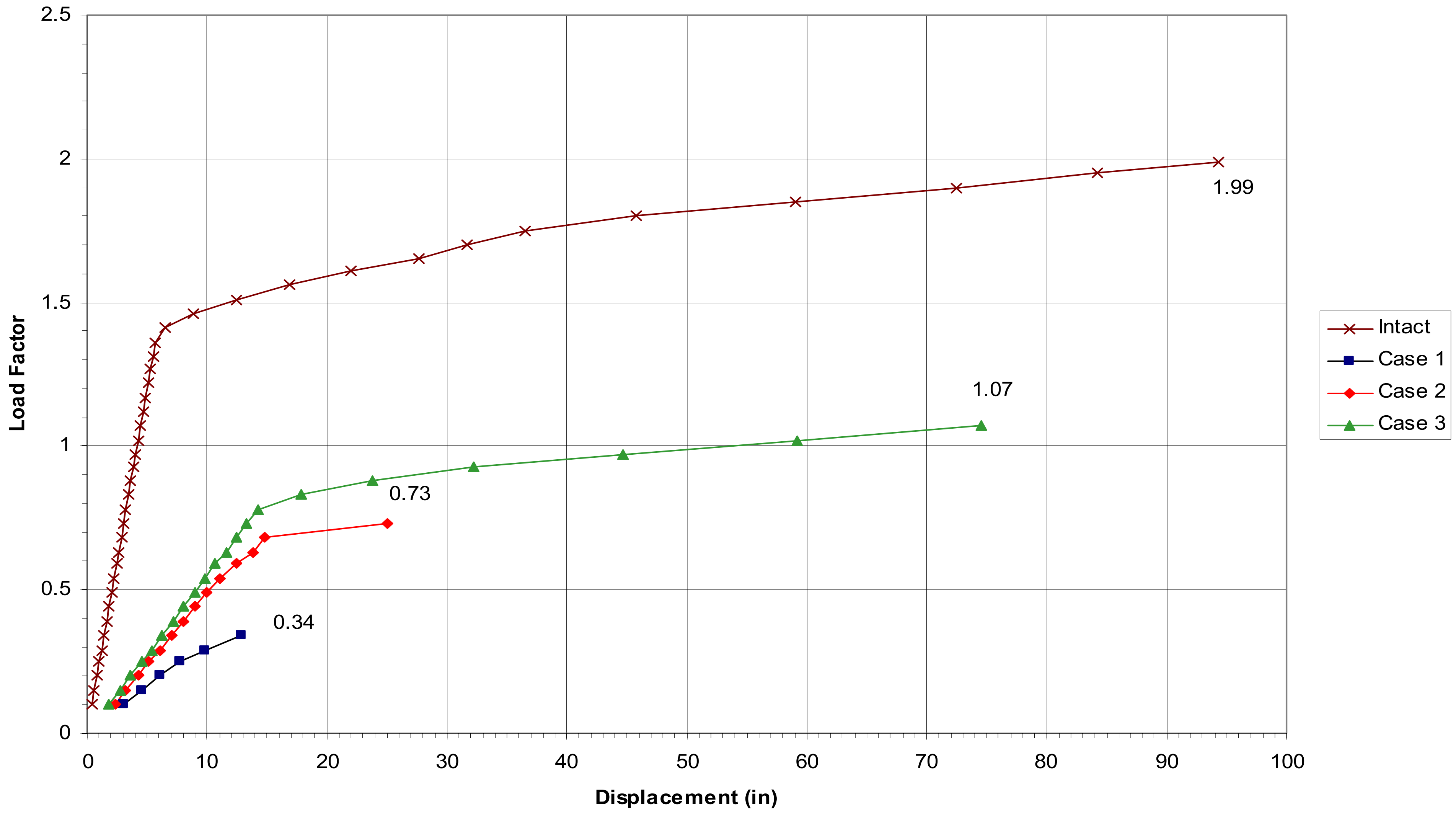


Figure 4.9 Load deflection curves for damaged single diagonal (tension) braced frames

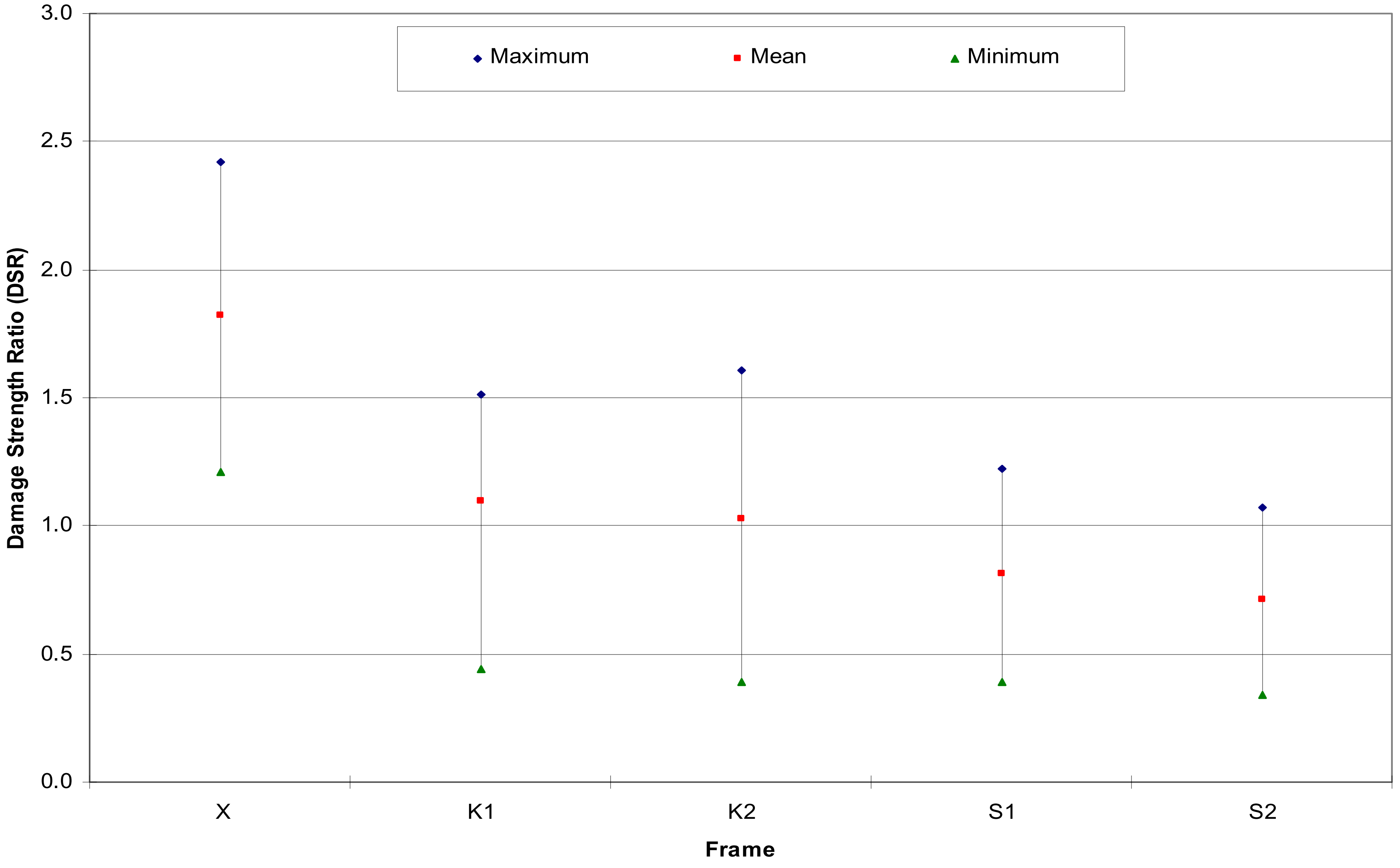


Figure 4.10 Comparison of damage strength ratios

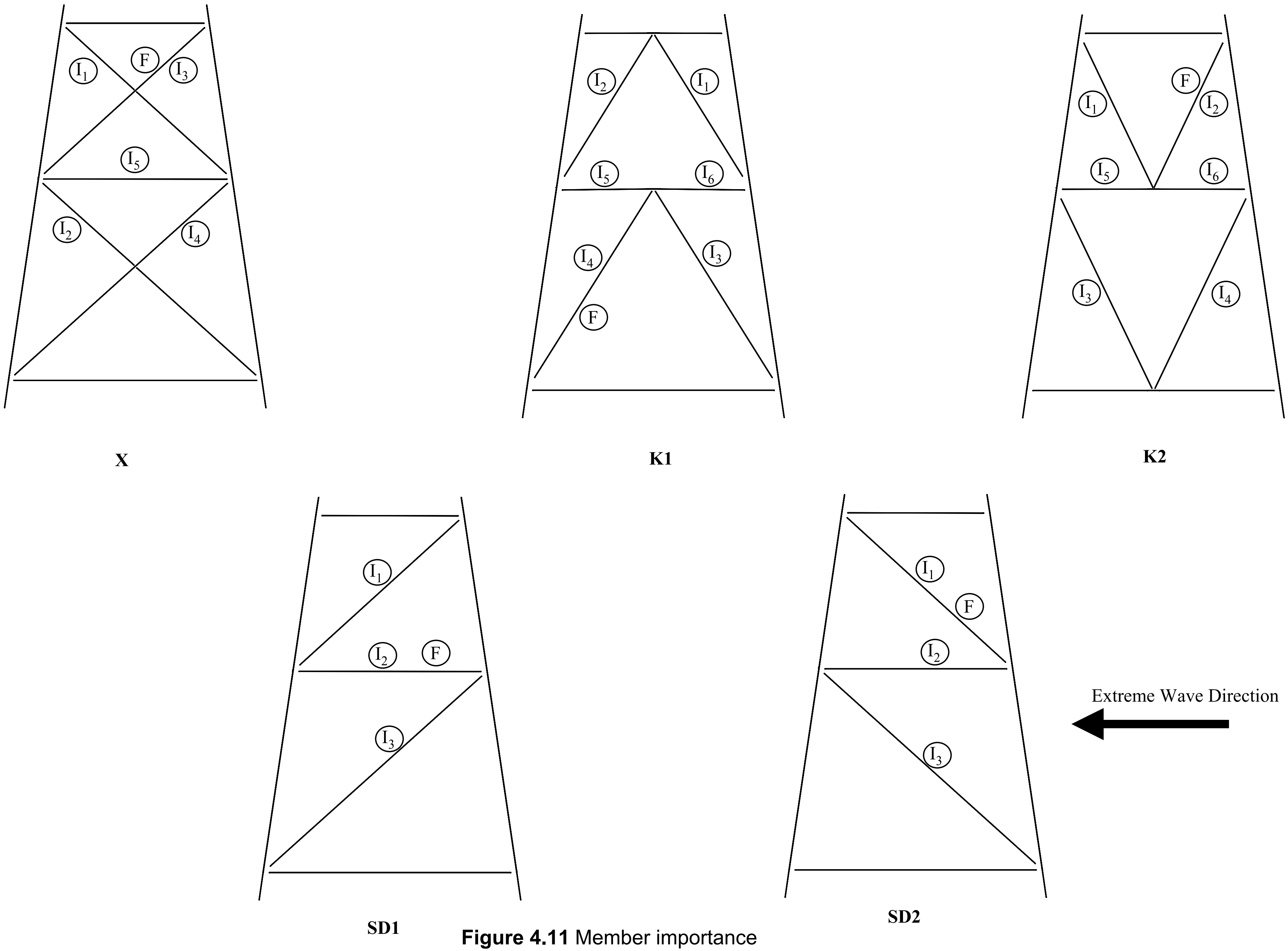


Figure 4.11 Member importance

Note: I_i indicates the importance of member in terms of damage. I_1 is the most important (largest reduction in capacity if this member is damaged).
F indicates the first member to yield in the pushover analysis of undamaged frame.

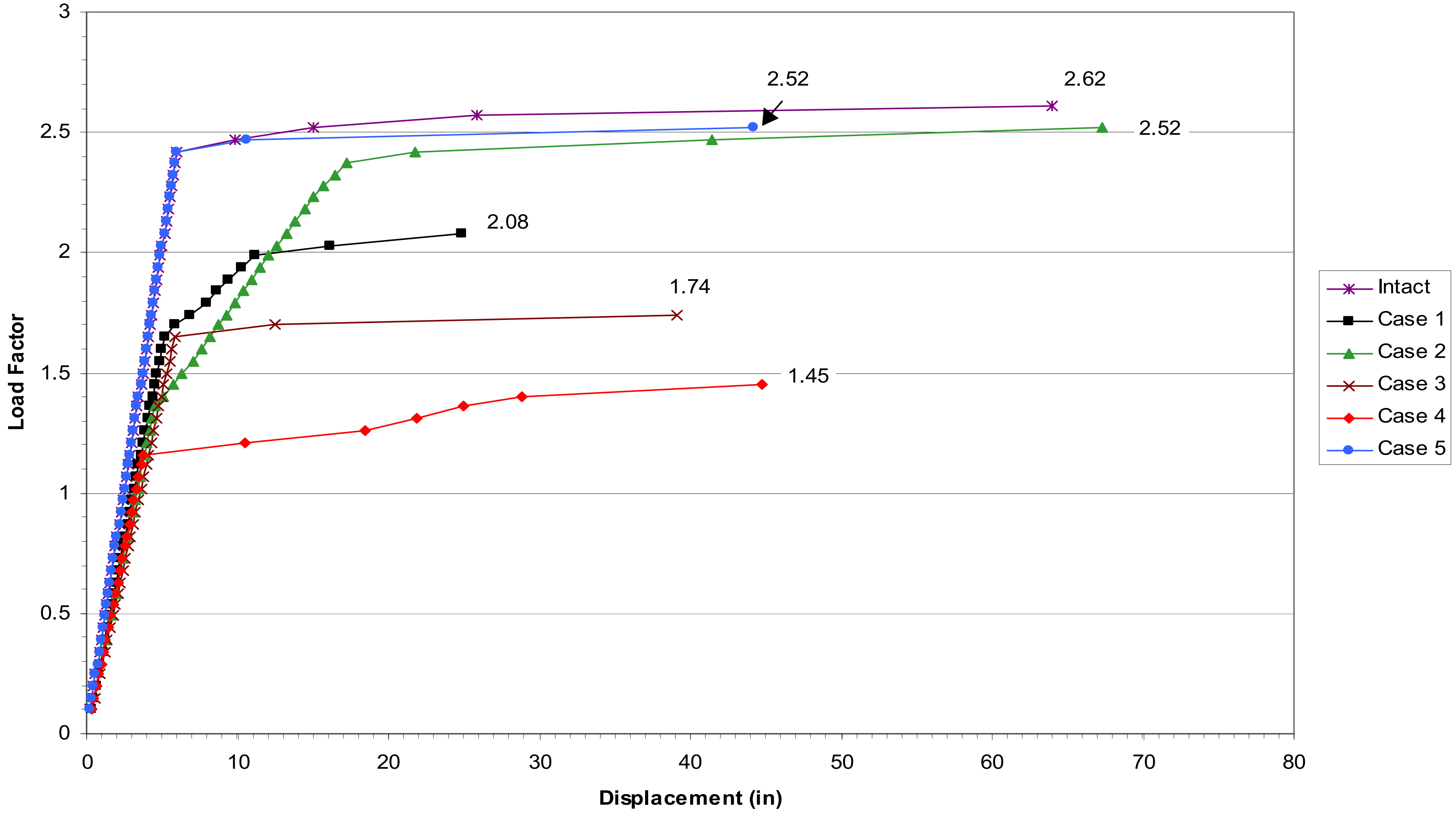
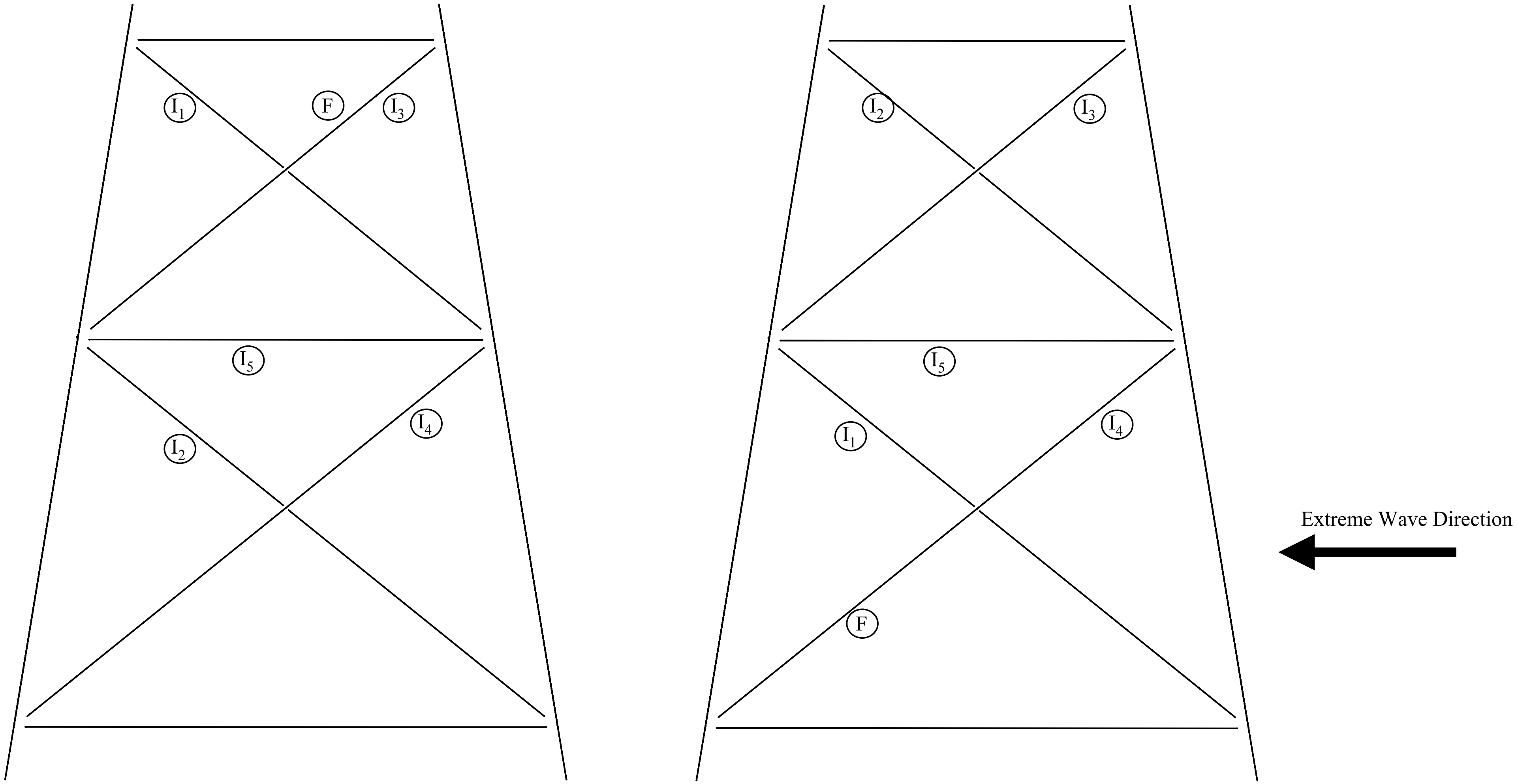


Figure 4.12 Load deflection curves for damaged X-braced frames (vertical diagonals in upper bay = Vertical diagonals in lower bay)



(a) X-braced frame
(vertical diagonals in lower bay > vertical diagonals in upper bay)

(a) X-braced frame
(vertical diagonals in lower bay = vertical diagonals in upper bay)

Figure 4.13 Effect of member sizing on member importance

Note: I_i indicates the importance of member in terms of damage. I_1 is the most important (largest reduction in capacity if this member is damaged).
F indicates the first member to yield in the pushover analysis of undamaged frame.

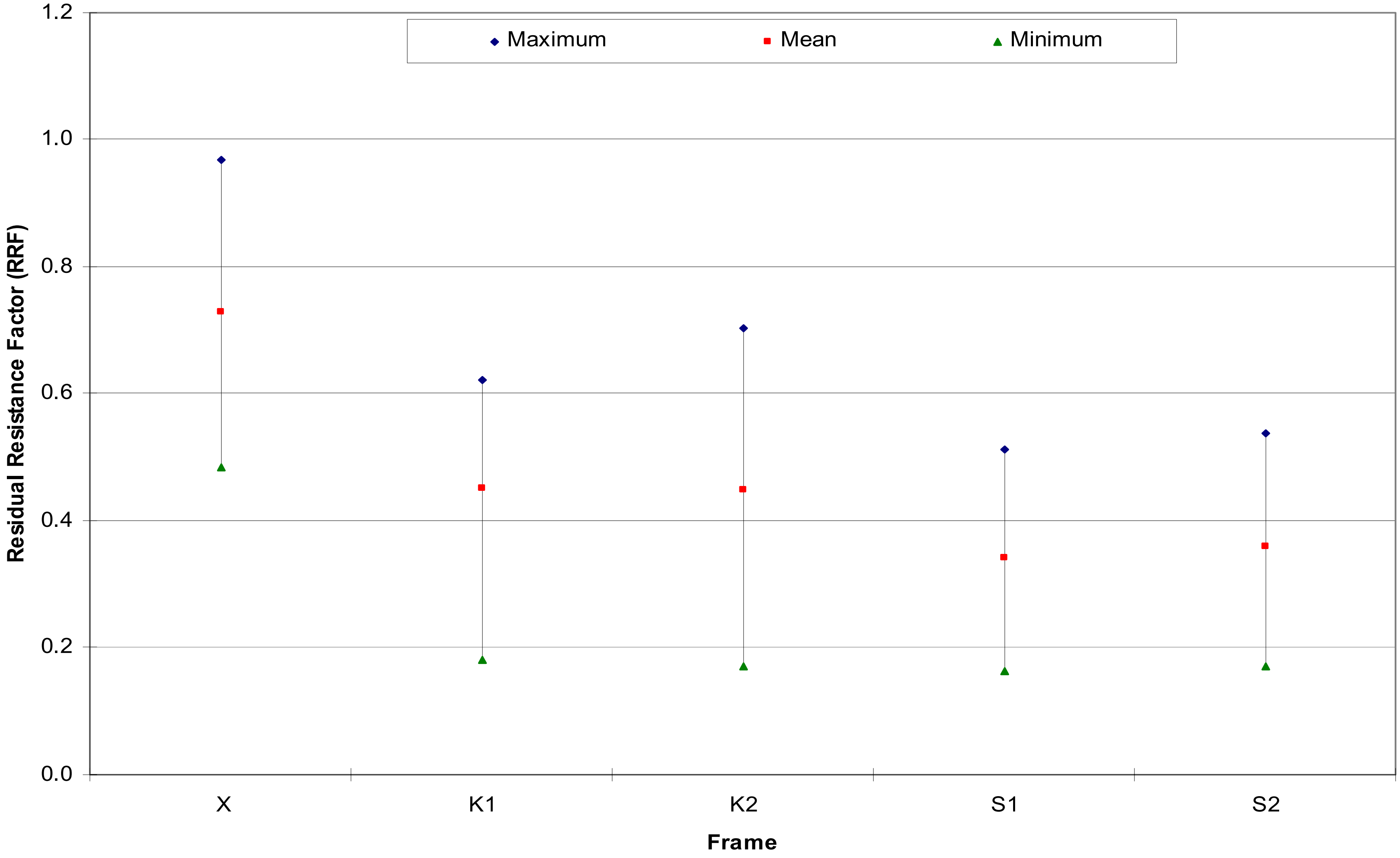


Figure 4.14 Comparison of residual resistance factors

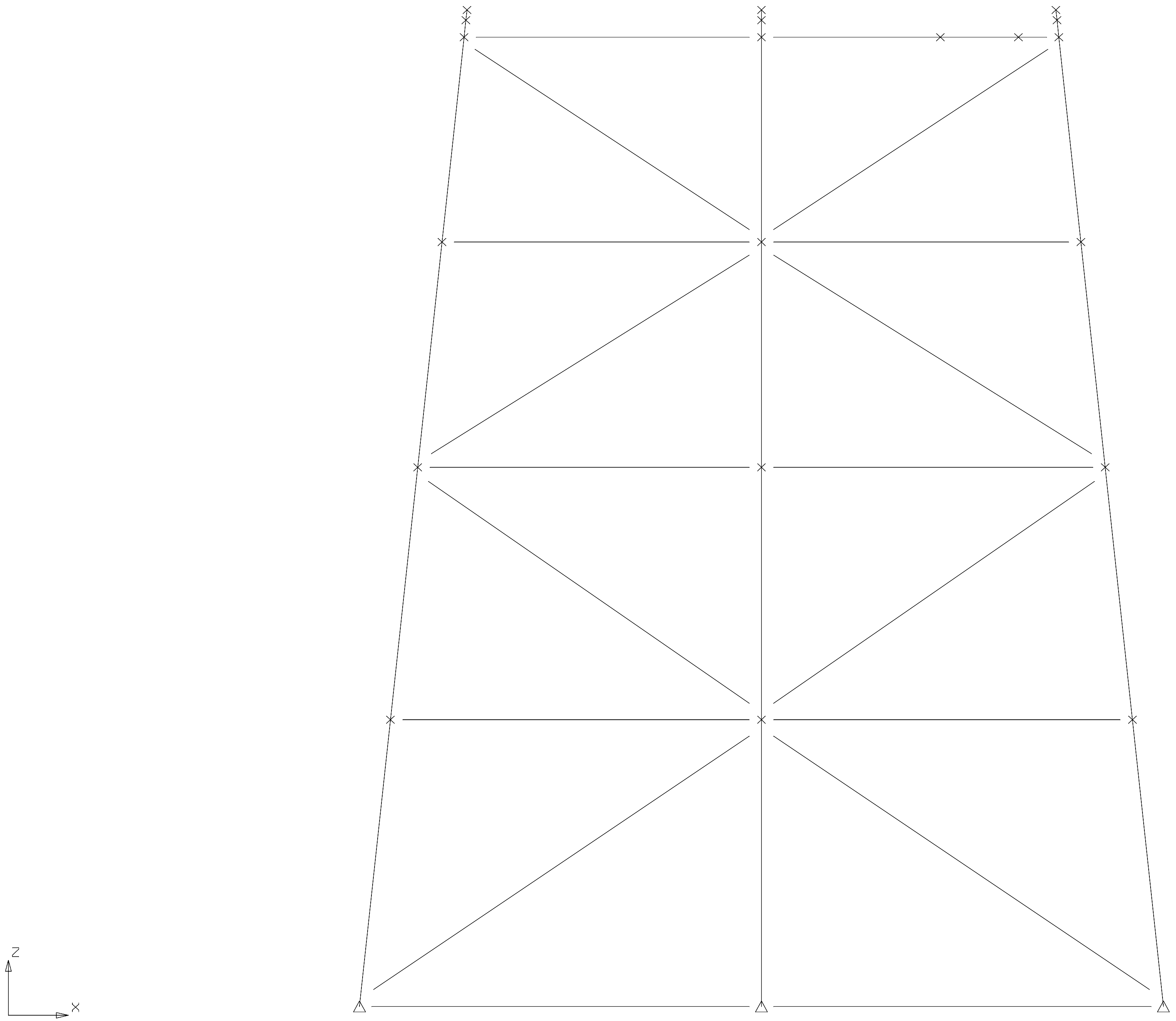


Figure 4.15 Diagonal-braced frame in an offshore platform

5.0 DATASET EVALUATION

5.1 GENERAL REMARKS

The dataset consists of approximately 190 pushover analysis results on a total of 62 platforms as described in Section 2. These include 28 four-leg, 2 six-leg, 25 eight-leg, and 8 other platforms. A survey of the data set has shown that there are differences in platforms with respect to the number of legs, vintage, bracing scheme, grouting of leg/pile annulus, wave in deck and number of conductors.

In this study, results in either end-on or broadside directions were used to study the effects of the pushover analyses (see Figure 2.1). The longitudinal frames of the platform resist the end-on loading, while its transverse frames resist the broadside loading.

A grouping based on the framing scheme (including longitudinal and transverse frames) results in a breakdown of frames as shown in Table 5.1. In the two-dimensional analyses, single diagonal bracing schemes with braces in tension and compression were treated differently. In practice, however, they are typically found in combination on any particular frame. In addition, hydrodynamic loads often come from different directions. Therefore, for the dataset review, tension and compression diagonals are combined as a single case. The single diagonal is abbreviated as SD throughout this section.

Table 5.1 Dataset: number of pushovers in each category

Number of Legs	Bracing Scheme			
	X	**K1**	**K2**	**SD**
<4	0	0	0	0
4	12	15	3	12
6	1	0	1	1
8	1	12	7	21
>8	2	4	1	7

The platforms were grouped into X, K1, K2, and SD bracing schemes for four, six, eight, and more than eight leg platforms as shown in Tables 5.2 to 5.5 (see page 41). Within each bracing scheme, the platforms are sub-grouped based on the vintage and further divided based on the presence or absence of grouting in the leg/pile annulus. Once the platforms are grouped, other factors are identified, such as wave-in-deck and the number of conductors. The methodology used to group the platforms for an X-bracing scheme is shown in Figure 5.1.

The following sections study the effects of different parameters discussed in Section 3 such as bracing scheme, vintage, leg/pile annulus grouting, wave-in-deck, and conductors.

5.2 DATASET REVIEW METHODOLOGY

Evaluation of the datasets was done using three methods. While the first evaluation involves general observation, the latter two are statistical analyses of the data. The three methods are:

5.2.1 General trends

From the resulting dataset, graphical comparisons were developed for design base shear, ultimate capacity of platforms, and reserve strength ratio (scattered plots) versus water depth. These parameters were plotted for four-leg, six-leg, eight-leg, more than eight-leg, and all platforms. The purpose of this exercise was to identify the trends in dataset.

5.2.2 Statistical analysis

This task involved a statistical analysis of the dataset. Two approaches were used: 1) an evaluation of the minimum, mean, and maximum (MMM) values, and 2) an evaluation of the cumulative distribution function (CDF) for various related subsets of the platforms (e.g., 4 leg, 8 leg, grouted, ungrouted, etc.). Further background on the CDF approach is provided below.

The CDF was used to represent the characteristics of the reserve strengths of a group of platforms. The reserve strength ratio (RSR) of the platforms was treated as a random variable. A “lognormal” distribution was assumed to represent the probabilistic characteristics of the reserve strength in this study. A random variable X has a lognormal distribution if $\ln X$ (natural logarithm of X) is normal. The probability density function (PDF) is:

$$f_X(x) \quad \frac{1}{\sqrt{2\pi}\zeta x} \exp\left[-\frac{1}{2} \left(\frac{\ln x - \lambda}{\zeta} \right)^2 \right] \qquad 0 \le x < \infty \quad =$$

Where $\lambda \quad E(\ln X)$ and $\zeta = \sqrt{Var(\ln X)}$ are, respectively, the mean and standard deviation of $\ln X$ where λ and ζ are the parameters of the distribution. The parameters of the lognormal distribution can be obtained from the mean and variance of the distribution as follows:

$$E(X) \quad \exp(\lambda + \frac{1}{2}\zeta^2)$$

$$Var(X) \quad E^2(X)(e^{\zeta^2} - 1)$$

The cumulative distribution function (CDF) is given by:

$$F_X(x) \quad P(X \le x) \quad \int_0^x f_X(\xi) d\xi \quad =$$

The coefficient of variation can be defined as the ratio of standard deviation to the mean of the dataset as

$$\text{cov} \quad \frac{\text{Standard Deviation}}{\text{Mean}}$$

When a particular dataset has less than three data-points, a coefficient of variation (COV) of 30% was assured to calculate the standard deviation and the cumulative distribution function of the dataset.

Throughout the study, it was assumed that a common measure of performance of a particular dataset will be the median of the dataset. The median is the value of a random variable at which the values above and below it are equally probable, i.e., if x_m is the median of X, then

$$F_X(x_m) \quad 0.50$$

Where $F_X(x)$ is the Cumulative Distribution Function (CDF) X.
In addition to the median, the 5, 70, and 95-percent RSRs of the datasets were also used as performance measures. For example, for a particular CDF, RSR_{70} means that 70% of the RSRs in the dataset are below the RSR_{70}.

5.3 GENERAL TREND RESULTS

Numerous plots were made of all of the platforms as a function of water depth versus design base shear, ultimate strength and RSR. These comparisons showed several levels of correlation and are discussed in this section.

Figure 5.2 (a) shows water depth versus design base shear for all platforms in the dataset. The data is fairly random with a large amount of variation for a given water depth. Figure 5.2 (b) shows a similar set of data except that the 6-leg and >8 leg cases (of which there are few) have been eliminated. The larger data subsets of 4 leg and 8 leg platforms have been individually combined with no relation to framing scheme. Also shown are median curves through each set of data. The 8 leg platforms have higher overall design base shear than the 4 leg platforms, as expected. These curves are useful as a first estimate of the base shear for platforms of these configurations and at these water depths.

Figure 5.3 (a) shows water depth versus ultimate strength for all platforms. Figure 5.3 (b) shows the data binned in a similar manner as described above for base shear. The 8 leg platforms show higher capacity than the 4 leg platforms, as expected. The plot is again useful as an initial estimate of platform capacity as a function of water depth and number of legs.

Figure 5.4 (a) shows water depth versus RSR for all platforms. Figure 5.4 (b) shows the data binned in a similar manner as the prior cases. For RSR however, the 8 leg RSRs are unexpectedly below the 4 leg RSRs. This is thought to be due to the presence of a large number of “new design” CBC 4 leg platforms at around 100 ft. water depth which have high capacity since they are designed to modern API criteria (compared to the generally older vintage 8 leg platforms).

In addition, there is a cluster of low capacity, 1960’s vintage in about 130-ft. water depth which tend to lower the 8 leg capacity curve. Figure 5.4(c) shows the curves with these platforms and the CBC platforms removed. In this case, with these “outlyers” taken out, the 8 leg platforms again have a larger RSR than the 4 leg platforms, as expected.

5.4 STATISTICAL ANALYSIS RESULTS

The MMMs and CDFs representing the probabilistic characteristics of reserve strength of all the datasets were used to compare the effect of the parameters described below for four, six, eight, and more than eight leg platforms. The parameters include:

- ***Bracing scheme***: CDFs of data sets of four, six, eight, and more than eight leg platforms were computed for different bracing schemes. The further to the right the curve, the more efficient is the bracing scheme as shown by the example in Figure 5.5. Wherever possible, the effect of bracing schemes was studied by comparing CDFs of datasets from different bracing schemes for a particular vintage in order to provide a consistent comparison for bracing scheme only.

- ***Vintage***: The effect of vintage was studied by comparing the CDFs of one particular bracing scheme for different vintages.

- ***Leg/pile annulus grout*:** To study the effect of grouting the leg/pile annulus, CDFs were computed for two datasets, grouted and ungrouted, for a particular vintage and bracing scheme.

- ***Wave-in-deck*:** The effect of wave-in-deck on the reserve strength of the platform was studied by comparing CDFs of two datasets having similar vintage and bracing characteristics, but differing in the wave-in-deck condition. The design wave inundates the deck in one dataset, but does not in the other.

5.4.1 Four-leg platforms

There are 42 pushover results in this category, including twelve X, fifteen K1, three K2, and, twelve SD frames. The effects of bracing scheme and vintage on the reserve strength of the platforms were studied using this dataset.

- *Effect of Bracing-Scheme*

Figures 5.5 and 5.6 illustrate the comparison of four-leg platforms with different bracing schemes. The datasets for X and SD frames contain platform cases which were designed as part of the API Consequence Based Criteria (CBC) study [13,14] in which the brace dimensions were optimized to arrive at an unity check of 1.0.

Figure 5.5 (a) compares the MMM RSRs of each dataset for platforms of all vintages grouped by framing type. The figure shows that the mean RSRs of SD and X frames are very close and are greater than those for K frames. Figure 5.5 (b) shows CDFs for different types of bracing schemes. The X-braced schemes are the most efficient (the CDF of X is the right most curve in Figure 5.5 (b)). Note that most of the X-braced CBC jackets in this category are optimized for the extreme storm strength. In practice, the platforms would likely have even higher RSRs once factors such as fatigue, load-out, transport, launch, installation, lifting and other items are incorporated into the design. These factors tend to increase the jacket member/joint size in several locations, which leads to an overall increase in jacket system capacity. Although these changes are not always substantial, they can be in the range of 15-20%.

Table 5.6 summarizes the RSRs having 5%, 50%, 70%, and 95% probability for X, K1, K2, and SD braced schemes of all vintages. X-braced frames have the highest RSRs with potential values greater than 4.0.

A comparison of different bracing schemes for a particular vintage, “1978-1993,” is shown in Figures 5.6 (a) and 5.6 (b). Figure 5.6 (a) shows the comparison of MMM of the datasets. Figure 5.6 (b) compares the CDFs of those datasets. Again, the better performance of X frames as compared to SD and K frames is apparent.

- *Effect of Vintage*

Figures 5.7-5.10 show the comparison of platforms for different vintages, for X, SD, K1 and K2-braced platforms, respectively. Figures 5.7 (a), 5.8 (a), 5.9 (a), and 5.10 (a) show the comparison of MMM RSRs of the datasets. Figures 5.7 (b), 5.8 (b), 5.9 (b), and 5.10 (b) compare the CDFs for the same datasets, respectively. Note that the further to the right the curve, the more efficient are the platforms of that vintage.

These figures show that, in most cases, the performance of the platforms increases for platforms of later vintage. In the case of X and SD bracing schemes, platforms installed between 1978-1993 seem to perform better. However, this can be attributed to the design of platforms from the “1999”CBC study where designs did not include fabrication, transportation, installation loads, etc. The platforms in the vintage group 1978-1993 from the API CBC study were designed to API 19th Edition, while platforms in the vintage group 1994-present from the API CBC study were designed to API 20th Edition.

5.4.2 Six-leg platforms

There are only two platforms with three types of frames (X, SD, K2) in this category. Figure 5.11 shows the CDFs for each of the three framing types. Figure 5.11 shows that the X-bracing scheme has a higher level of reserve strength compared to the K2-and SD frames. The SD and K2 are the end-on and broadside frames of the platform, respectively. Often, the capacity of the platform for the end-on direction pushover is expected to be better than that for the broadside direction.

Table 5.6 shows the 5, 50, 70, and 95 percentile RSRs for the above bracing schemes. The median for the X, SD, and K2 bracing schemes are 2.58, 0.96, and 1.59, respectively. These values demonstrate the better reserve strength characteristics of the X bracing scheme.

5.4.3 Eight-leg platforms

There are 41 pushover results in this category, including one X, twenty-one SD, twelve K1, and seven K2 frames. Since there are so many platforms of different configuration in this category there was a good opportunity to study the effects of other parameters (besides bracing and vintage), including grouting of the leg/pile annulus and wave-in-deck loading. These are described below:

- *Effect of Bracing-Scheme*

Figure 5.12 (a) shows the comparison of minimum, mean, and maximum RSRs for the datasets of X, SD, K1, and K2 bracing types. Figure 5.12 (b) shows the cumulative distribution functions (CDF) for these bracing schemes. These figures illustrate that the X braced platforms have greater reserve strength as compared to the other bracing schemes.

Table 5.6 summarizes the 5%, 50%, 70%, and 95% probability RSRs for X, SD, K1, and K2 frames. These values demonstrate that the reserve strength of X-braced platforms is more than that of other braced frames. The two-dimensional studies described in Section 4 have demonstrated that the X-braced frames offer alternative load paths to resist the loads.

- *Effect of Vintage*

Figures 5.13-5.14 show the effect of vintage on platforms with SD and K1 bracing schemes, respectively. Figures 5.13 (a) and 5.14 (a) show the comparison of MMM RSRs of the data sets. The CDFs for these datasets are compared in Figures 5.13 (b) and 5.14 (b), respectively. These figures illustrate that performance of the platforms improves for later vintage groups. As previously discussed, an improvement in design practices and technologies in recent years have contributed to the increase in platform reserve strength.

- *Effect of Leg/Pile Annulus Grout*

In order to study the effects of grouting, the group of eight-leg K1-braced platforms installed before 1964 has been divided into two subgroups based on whether the leg/pile annulus is grouted or not. Figure 5.15 (a) shows the comparison of MMM RSRs and Figure 5.15 (b) shows the CDFs of these datasets. These figures illustrate that leg/pile annulus grouting contributes to the increase in reserve strength of the platforms.

A quantitative comparison of platforms P38 and P41 is shown in Table 5.7 for pushovers in end on, diagonal, and broadside directions. While platform P40 has its leg/pile annuli filled with grout, P38 has ungrouted leg/pile annuli. For these platforms, leg/pile annulus grouting seems to have increased the reserve strength by approximately 10%.

- *Effect of Wave-in-Deck*

API 20th edition 100-year wave criteria has been used as a standard measure for the wave-in-deck. In other words, for each platform, the wave-in-deck was determined based on whether the 100-year wave inundates the deck or not. The particular amount of wave-in-deck loads is based upon the amount of deck inundation based upon the comparison of the deck elevation and the wave crest elevation.

The effect of wave-in-deck was studied for single diagonal-braced platforms, designed before 1964. Figures 5.16 (a) and 5.16 (b) show the comparison of platforms with and without the wave inundation in the deck. Figure 5.16 (a) compares the MMM RSRs of the datasets and Figure 5.16 (b) shows their CDFs. These figures illustrate that the wave-in-deck loads result in decrease in RSR.

5.4.4 More than eight-leg platforms

This dataset consists of one 10 leg, one 12 leg, one 16 leg, four 8-leg with two 3-leg auxiliary platforms, and one 36-leg platform. There are fourteen pushover results in this category, including two X, seven SD, four K1, and one K2 frames.

Figure 5.17 (a) shows the comparison of MMM RSRs of the X, SD, K1, and K2 datasets. The CDFs for the above datasets are presented in Figure 5.17 (b). These figures illustrate that X-braced frames perform better than the other bracing-schemes.

Table 5.6 summarizes the 5%, 50%, 70%, and 95% probability RSRs for X, K1, and SD braced schemes for all vintages. These values demonstrate the better reserve strength of X braced platforms as compared to other bracing schemes. The RSRs shown for the >8 leg platforms are below those for platforms with a lower number of legs. This is contrary to the trend shown in a comparison of 4, 6, and 8 leg platforms where the RSR increases with the number of legs. This is because the particular dataset of >8 leg platforms consists of mostly older structures including 1950’s vintage and unusual configurations (vertical legs) that result in lower RSRs.

Table 5.2 Four leg platforms

X Bracing Scheme								Single Diagonal Bracing Scheme								K1 Bracing Scheme								K2 Bracing Scheme							
Vintage	**Grout**	**Platform**	**WD**	**WID**	**Con.**	**RSR**	**Direction**	**Vintage**	**Grout**	**Platform**	**WD**	**WID**	**Con.**	**RSR**	**Direction**	**Vintage**	**Grout**	**Platform**	**WD**	**WID**	**Con.**	**RSR**	**Direction**	**Vintage**	**Grout**	**Platform**	**WD**	**WID**	**Con.**	**RSR**	**Direction**
70-77	**No**	P08	160	No	8	1.18	Broadside	**64-69**	**Yes**	P49	140	Yes	0	1.4	EndOn	**<=64**	**Yes**	P31	170	Yes	0	0.83	EndOn	**<=64**	**Yes**	P49	140	Yes	0	0.7	Broadside
78-93	**No**	P02	111	No	6	2.63	East	**78-93**	**Yes**	P13	219	No	6	3.35	Broadside			P31	170	Yes	0	1.88	Broadside	**78-93**	**No**	P22	95	No	4	1.26	184
		P02	111	No	6	3.69	South			P13	219	No	6	2.02	South		**No**	P42	144	No	0	1.23	EndOn			P22	95	No	4	0.67	290
		P04	111	No	6	2.01	South		**No**	P17	161	N/A	9	2.25	East			P42	144	No	0	0.76	Broadside								
		P04	111	No	6	3.12	West			P05D	111	No	6	1.75	Broadside	**64-69**	**Yes**	P07	103	No	10	0.55	Broadside								
		P05A	111	No	6	1.70	South			P05E	111	No	6	2.5	EndOn	**69-77**	**Yes**	P25	61	No	N/A	0.99	Orthogonal								
		P05A	111	No	6	2.85	West			P05E	111	No	6	2.05	EndOn			P26 A	180	N/A	12	2.1	West								
94-	**No**	P01	111	No	6	1.85	East			P17	161	N/A	9	2.77	South			P26 B	180	N/A	22	1.38	West								
		P01	111	No	6	2.85	South			P36	137	N/A	6	1.64	South			P26 C	180	N/A	28	1.2	West								
		P03	111	No	6	2.05	East	**94-**	**No**	P05B	111	No	6	1.90	East			P26 C	180	N/A	28	1.51	North								
		P03	111	No	6	2.50	South			P05C	111	No	6	2.50	South			P50	61	N/A	28	1.45	Orthogonal								
	Yes	P56	475.72	No	22	2.04	South			P05C	111	No	6	2.10	EndOn		**No**	P09	182	No	10	1.66	EndOn								
																		P09	182	No	10	1.02	Broadside								
																78-93	**Yes**	P57	164	No	7	1.7	East								
																		P57	164	No	7	2.31	S								

Table 5.3 Six leg platforms

X Bracing Scheme								Single Diagonal Bracing Scheme								K1 Bracing Scheme								K2 Bracing Scheme							
Vintage	**Grout**	**Platform**	**WD**	**WID**	**Con.**	**RSR**	**Direction**	**Vintage**	**Grout**	**Platform**	**WD**	**WID**	**Con.**	**RSR**	**Direction**	**Vintage**	**Grout**	**Platform**	**WD**	**WID**	**Con.**	**RSR**	**Direction**	**Vintage**	**Grout**	**Platform**	**WD**	**WID**	**Con.**	**RSR**	**Direction**
64-69	**No**	P51	118			2.72	EndOn	**64-69**	**Yes**	P35	130			1.69	EndOn									**64-69**	**Yes**	P35	130			1.03	Broadside

WD - Water Depth
WID - Wave in Deck
Con. - Conductors
RSR - Reserve Strength Ratio
NA - Not Available

Table 5.4 Eight leg platforms

X Bracing Scheme								Single Diagonal Bracing Scheme								K1 Bracing Scheme								K2 Bracing Scheme							
Vintage	Grout	Platform	WD	WID	Con.	RSR	Direction	Vintage	Grout	Platform	WD	WID	Con.	RSR	Direction	Vintage	Grout	Platform	WD	WID	Con.	RSR	Direction	Vintage	Grout	Platform	WD	WID	Con.	RSR	Direction
NA	**No**	P27	310	No	10	2.80	Broadside	**<64**	**Yes**	P28	140	No	10	0.75	EndOn	**<64**	**Yes**	P28	140	No	10	0.56	Broadside	**64-69**	**Yes**	P34	176	Yes	8	1.04	Broadside
										P33	145	Yes	8	0.95	EndOn			P33	145	Yes	8	0.82	Broadside			P37	107	No	12	2.48	Broadside
										P40	180	Yes	8	1.32	EndOn			P40	180	Yes	8	0.93	Broadside			P48	141	No	16	1.48	Broadside
										P47	140	No	0	1.11	EndOn			P44	61	N/A	N/A	1.05	Broadside			P55	184	No	14	2.19	Broadside
									No	P38	137	Yes	8	0.84	EndOn			P47	140	No	0	0.86	Broadside	**64-69**	**No**	P52	160	No	11	0.94	EndOn
										P45	140	Yes	8	0.91	EndOn		**No**	P38	137	Yes	8	0.85	Broadside	**69-77**	**Yes**	P11	263	No	18	1.26	Broadside
										P46	140	Yes	16	0.66	EndOn			P45	140	Yes	8	0.84	EndOn	**78-93**	**No**	P19	125	N/A	N/A	5.01	Broadside
								64-69	**Yes**	P34	176	Yes	8	0.91	EndOn			P46	140	Yes	16	0.54	Broadside								
										P37	107	No	12	1.31	EndOn	**64-69**	**No**	P18	247	No	14	1.50	Broadside								
										P48	141	No	16	0.70	EndOn			P41	137	N/A	0	1.31	Broadside								
										P55	184	No	14	1.60	EndOn	**69-77**	**Yes**	P12	300	No	24	3.24	Broadside								
									No	P18	247	No	14	1.11	EndOn		**No**	P10	255	No	21	1.39	Broadside								
									NA	P41	137	N/A	0	0.64	EndOn																
										P52	160	No	11	1.80	EndOn																
									NA	P53	103	N/A	N/A	0.60	Broadside																
								69-77	**Yes**	P11	263	No	18	1.12	EndOn																
									No	P10	255	No	21	1.31	EndOn																
								78-93	**Yes**	P54	211	No	24	1.55	EndOn																
										P54	211	No	24	2.25	Broadside																
									No	P19	125	N/A	N/A	4.20	EndOn																
								NA	No	P27	310	No	10	2.50	EndOn																

Table 5.5 Platforms with more than eight legs

X Bracing Scheme								Single Diagonal Bracing Scheme								K1 Bracing Scheme								K2 Bracing Scheme							
Vintage	Grout	Platform	WD	WID	Con.	RSR	Direction	Vintage	Grout	Platform	WD	WID	Con.	RSR	Direction	Vintage	Grout	Platform	WD	WID	Con.	RSR	Direction	Vintage	Grout	Platform	WD	WID	Con.	RSR	Direction
<64	**Yes**	P14	88	No	14	2.68	EndOn	**<64**	**Yes**	P29	187	Yes	16	0.52	End On	**<64**	**Yes**	P29	187	Yes	16	0.85	Broadside	64-69	Yes	P32	168	Yes	0	1.83	Broadside
		P14	88	No	14	1.94	Broadside			P39	128	Yes	16	1.13	End On			P39	128	Yes	12	0.77	Broadside								
									No	P30	160	Yes	9	0.52	End On		**No**	P30	160	Yes	9	1.27	Broadside								
										P43	139	Yes	N/A	0.56	EndOn			P43	139	Yes	N/A	1.06	Broadside								
										P23	37	No	N/A	1.47	End On																
										P23	37	No	N/A	1.99	Broadside																
								64-69	**Yes**	P32	168	Yes	0	0.99	End On																

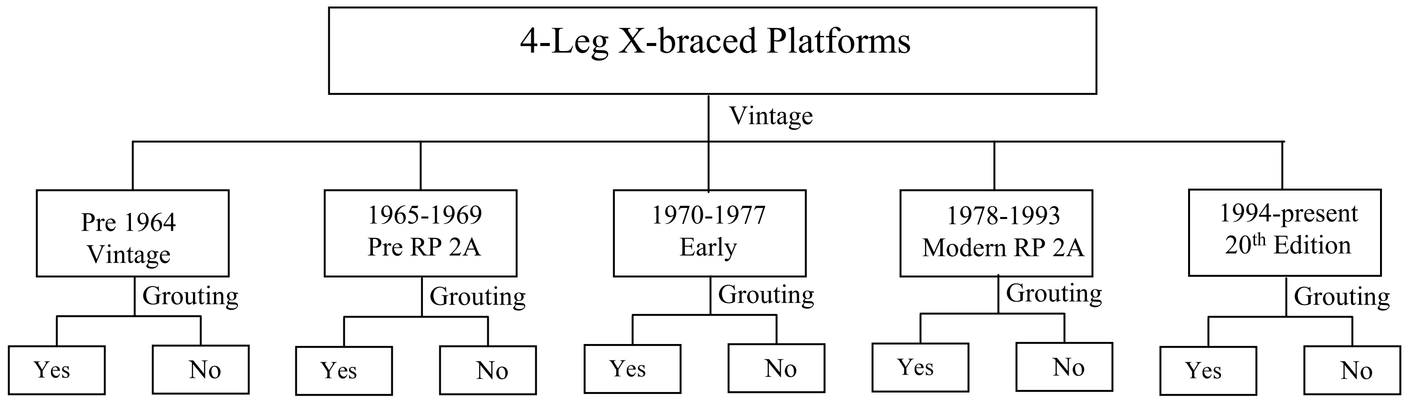
WD - Water Depth
WID - Wave in Deck
Con. - Conductors
RSR - Reserve Strength Ratio
NA - Not Available

Table 5.6 Performance of platforms as measured by RSR (Probability RSR <= Value shown)

Bracing	**5%**	**50%**	**70%**	**95%**
4 Leg Platforms				
X	1.35	2.27	2.67	3.74
K1	0.65	1.28	1.57	2.43
K2	0.47	0.84	1.01	1.52
SD	1.44	2.13	2.41	3.12
6 Leg Platforms				
X	1.58	2.58	3.01	4.20
K1				
K2	0.58	0.96	1.13	1.58
SD	0.97	1.59	1.56	2.60
8 Leg Platforms				
X	1.63	2.65	3.10	4.32
K1	0.46	1.02	1.31	2.22
K2	0.65	1.74	2.36	4.47
SD	0.52	1.23	1.61	2.87
>8 Leg Platforms				
X	1.34	2.18	2.56	3.56
K1	0.67	0.97	1.09	1.39
K2				
SD	0.38	0.90	1.20	2.15

Table 5.7 Effect of grouting

Platform	**RSR**		
	End-On	**Diagonal**	**Broadside**
P38	0.84	0.77	0.85
P40	1.32	0.88	0.93
Relative (P40/P38)	1.57	1.14	1.09



Once the platforms grouped based on grouting, other factors are flagged such as, the wave -in-deck and the number of conductors.

Figure 5.1 Demonstration of grouping of platforms for X-braced 4 leg platforms

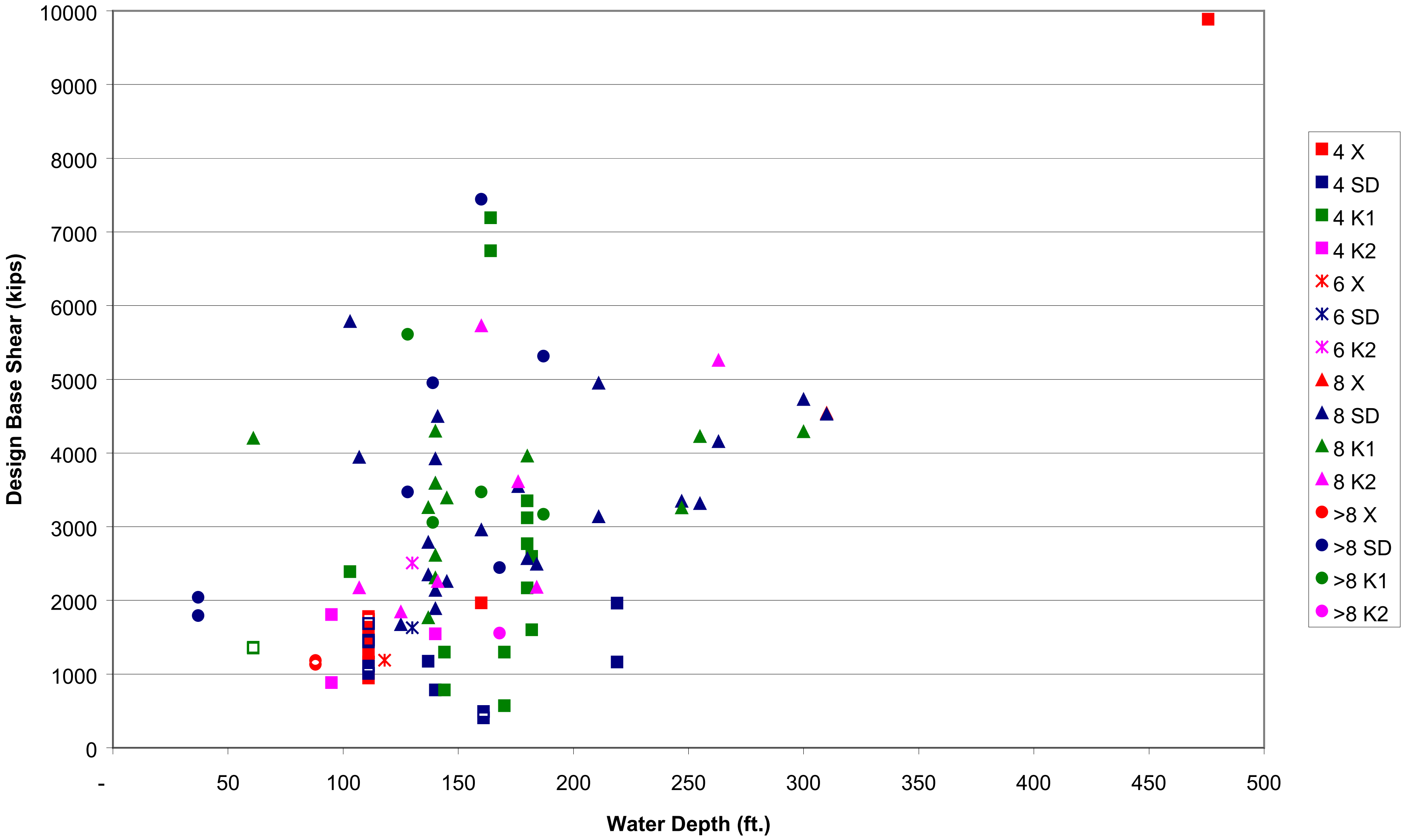


Figure 5.2 (a) Water depth vs design base shear – all platforms

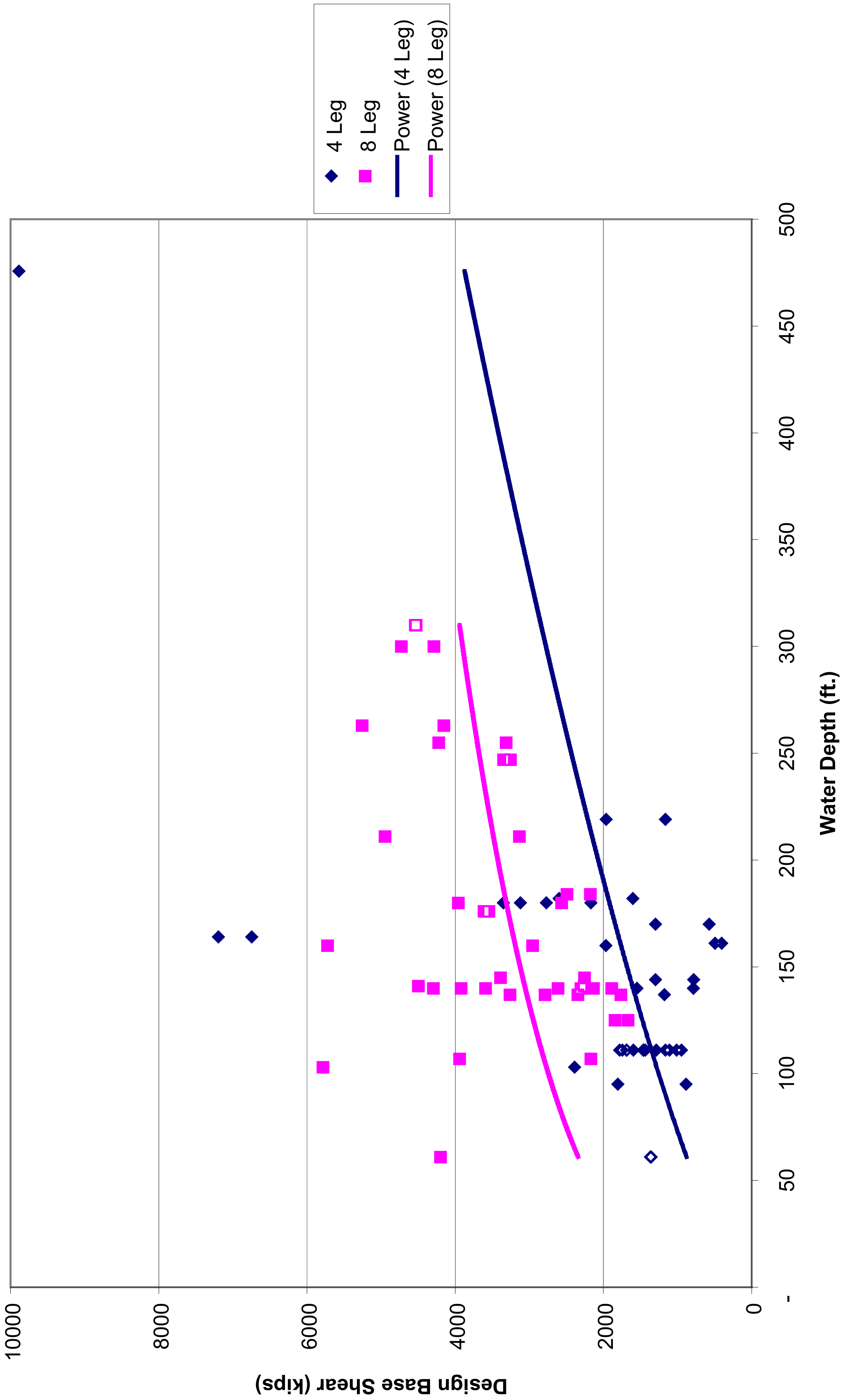


Figure 5.2 (b) Water depth vs design base shear – select platforms

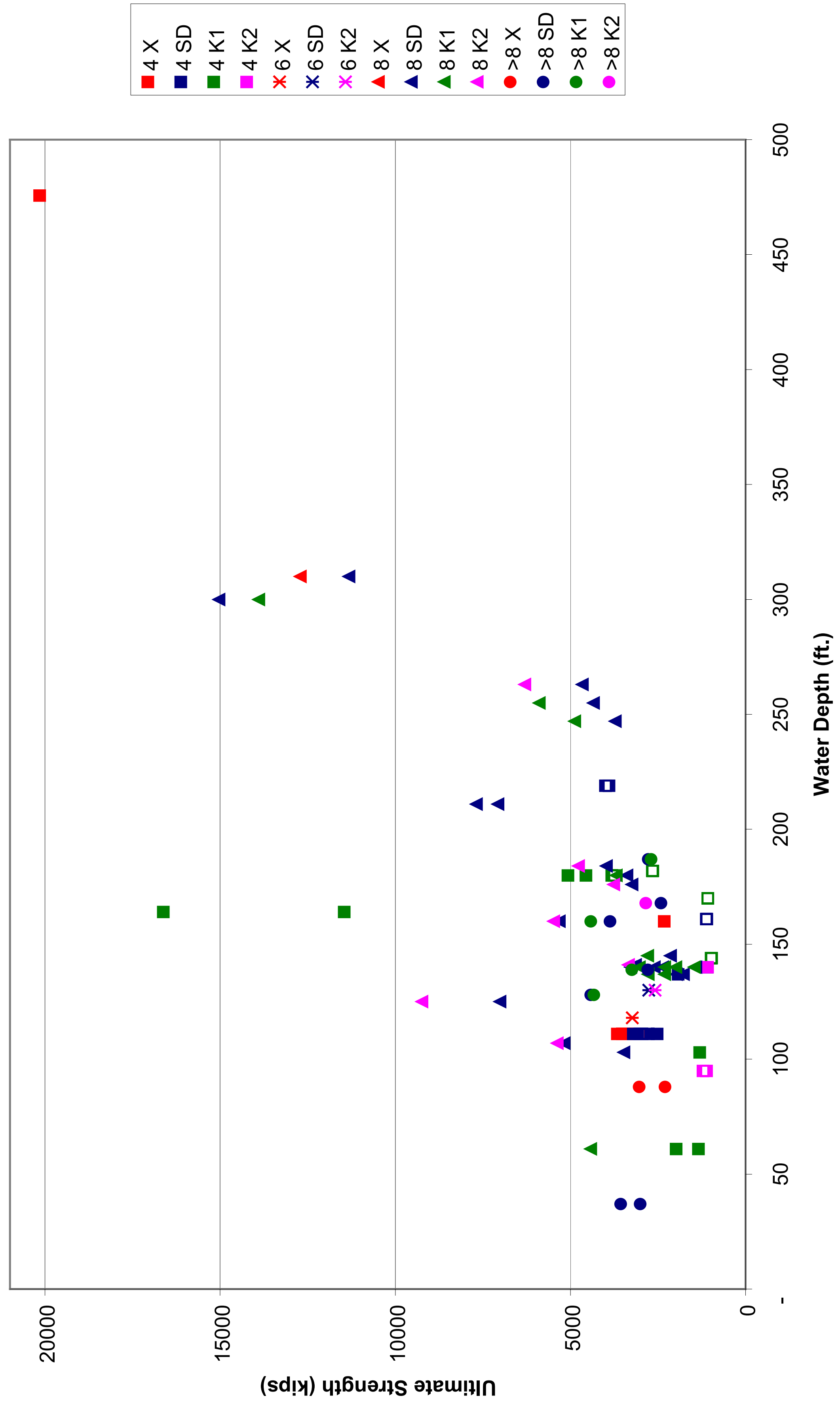


Figure 5.3 (a) Water depth vs ultimate strength – all platforms

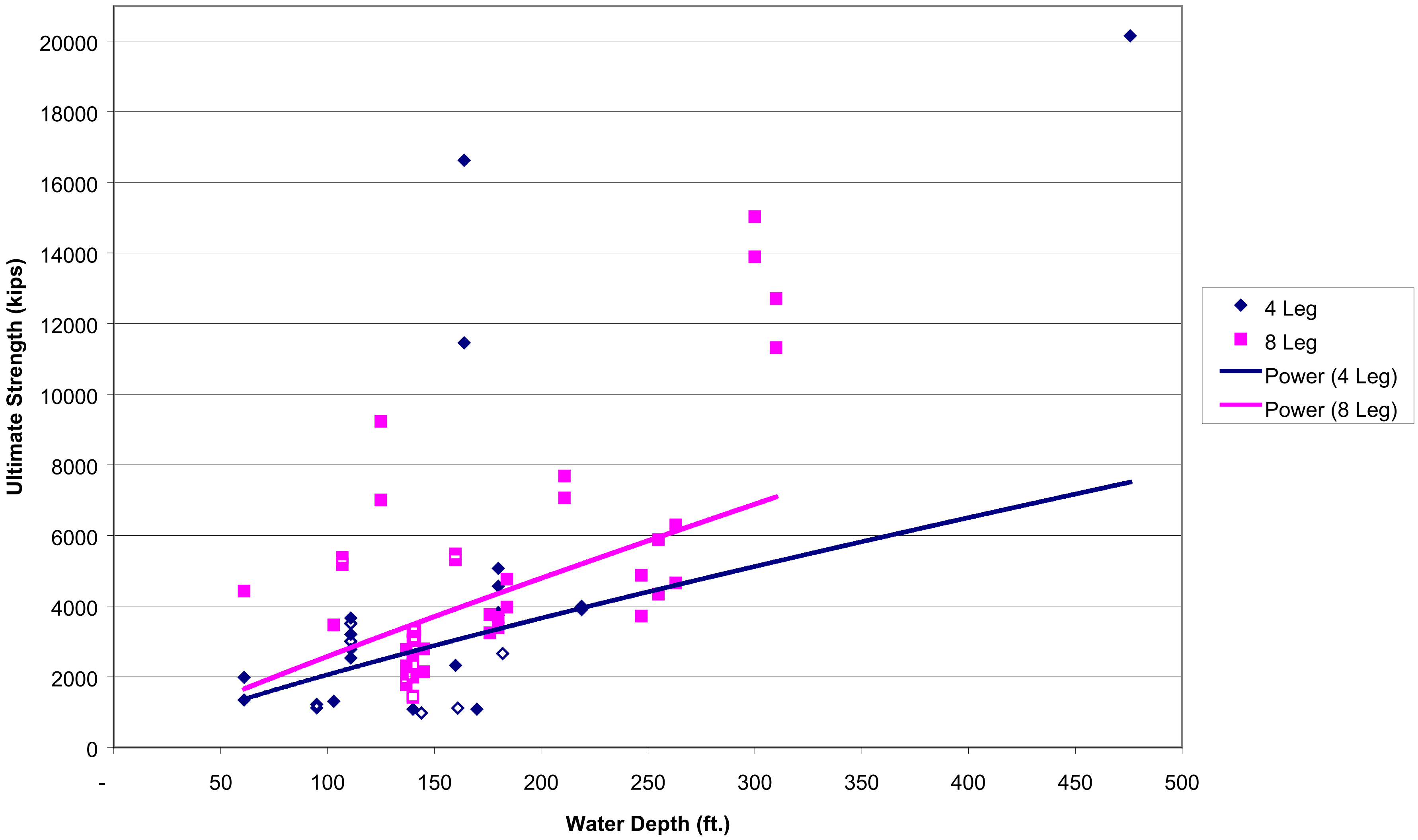


Figure 5.3 (b) Water depth vs ultimate strength – select platforms

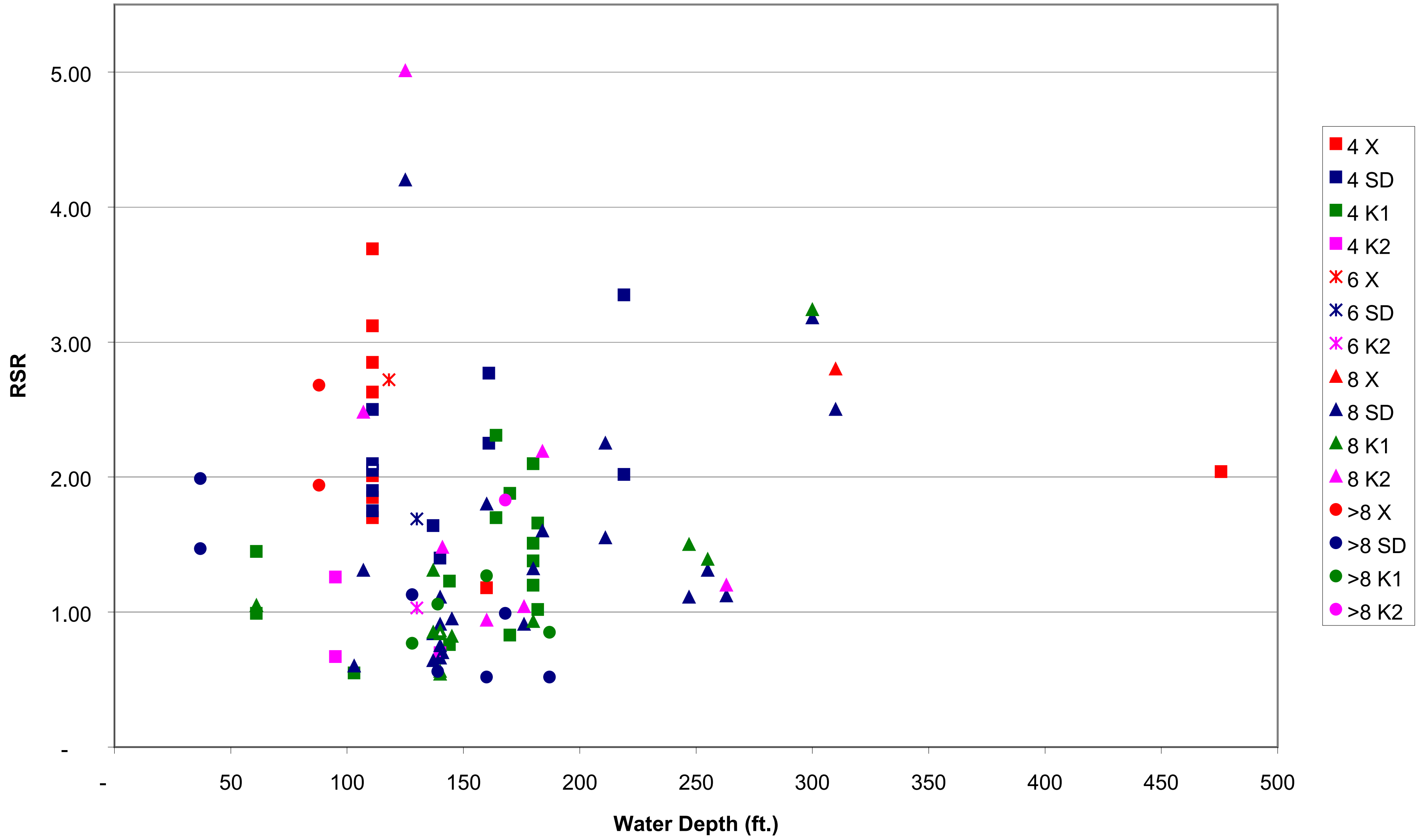


Figure 5.4 (a) Water depth vs RSR – all platforms

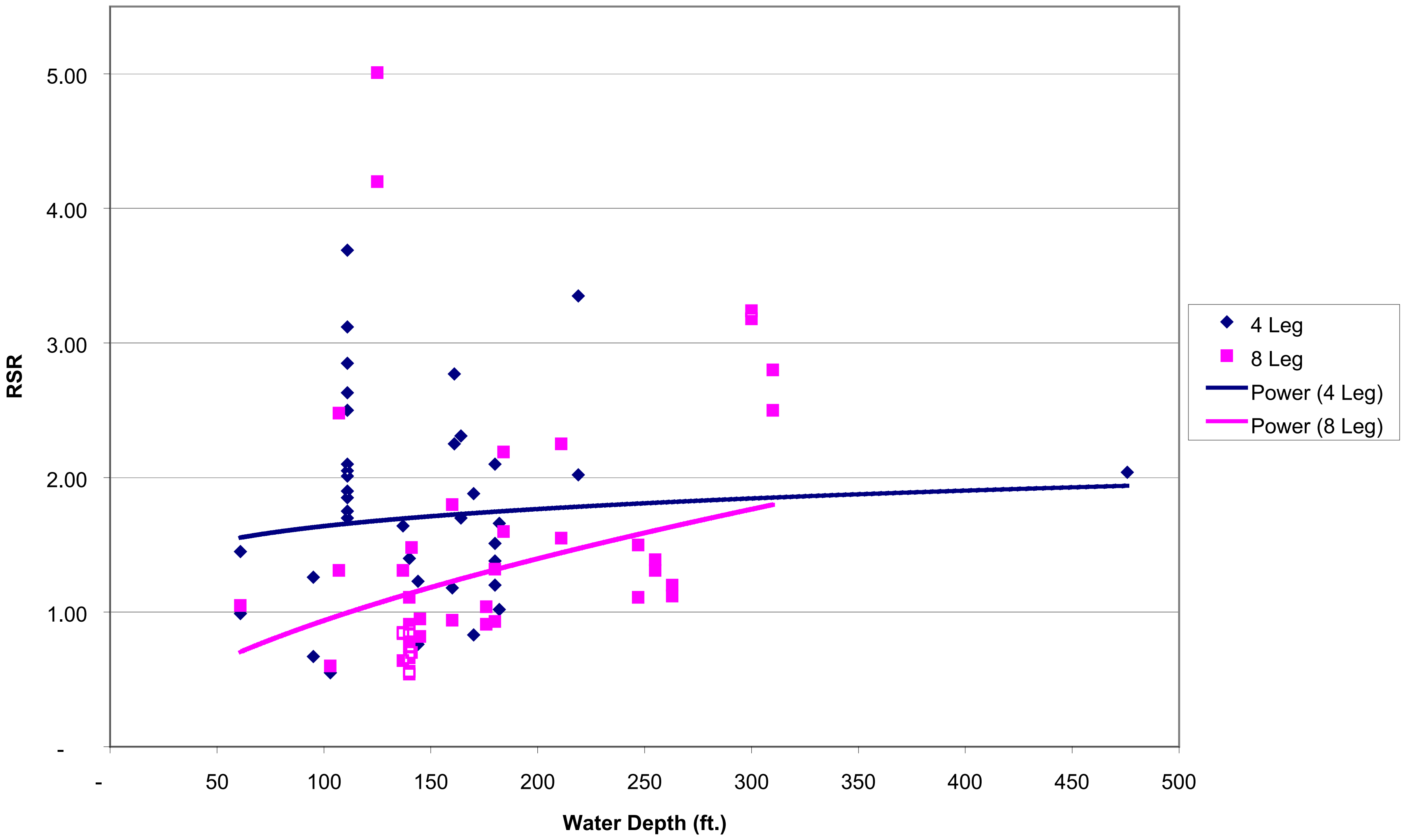


Figure 5.4 (b) Water depth vs RSR – select platforms

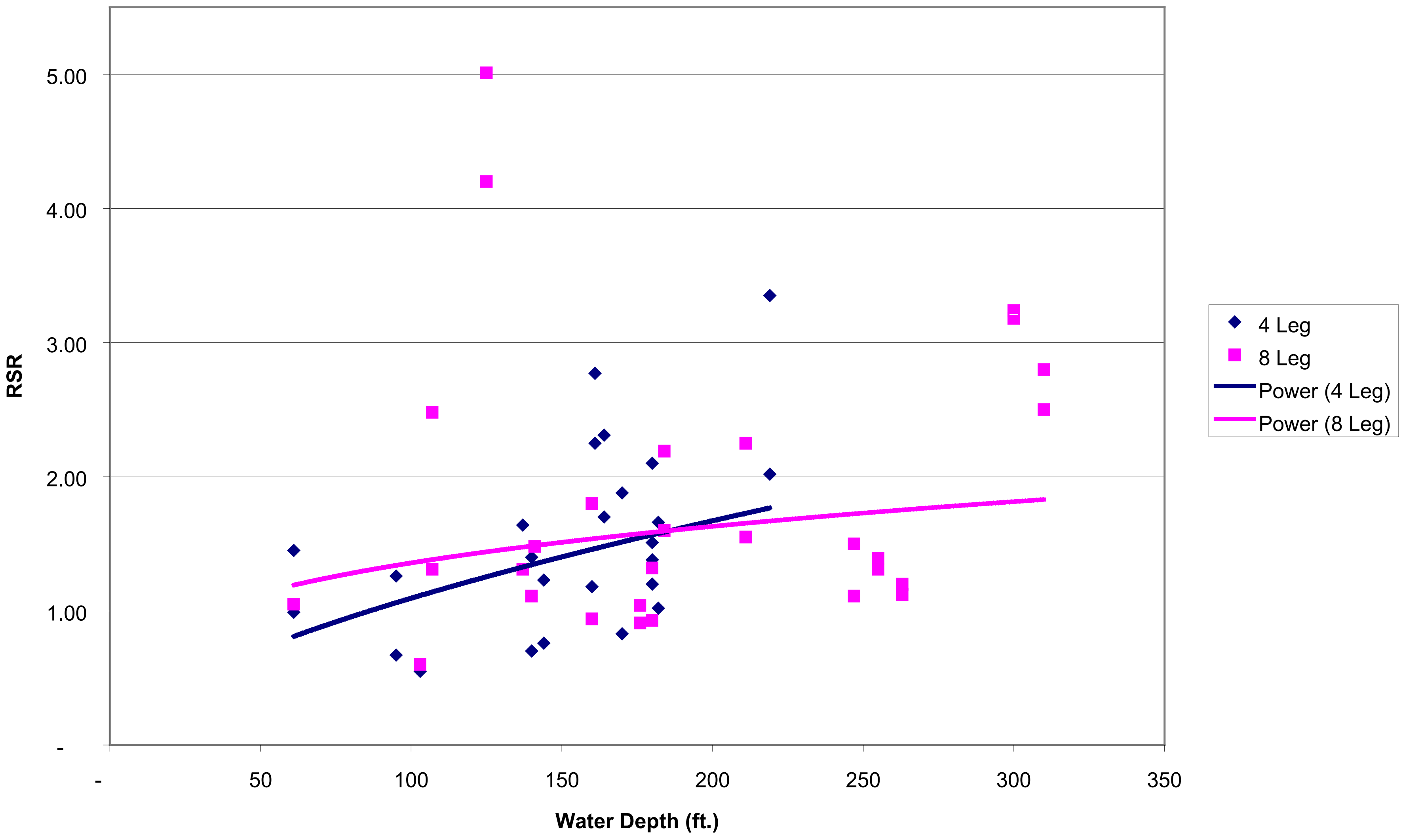


Figure 5.4 (c) Water depth vs RSR – select platforms without CBC and 1960s 8 leg platforms

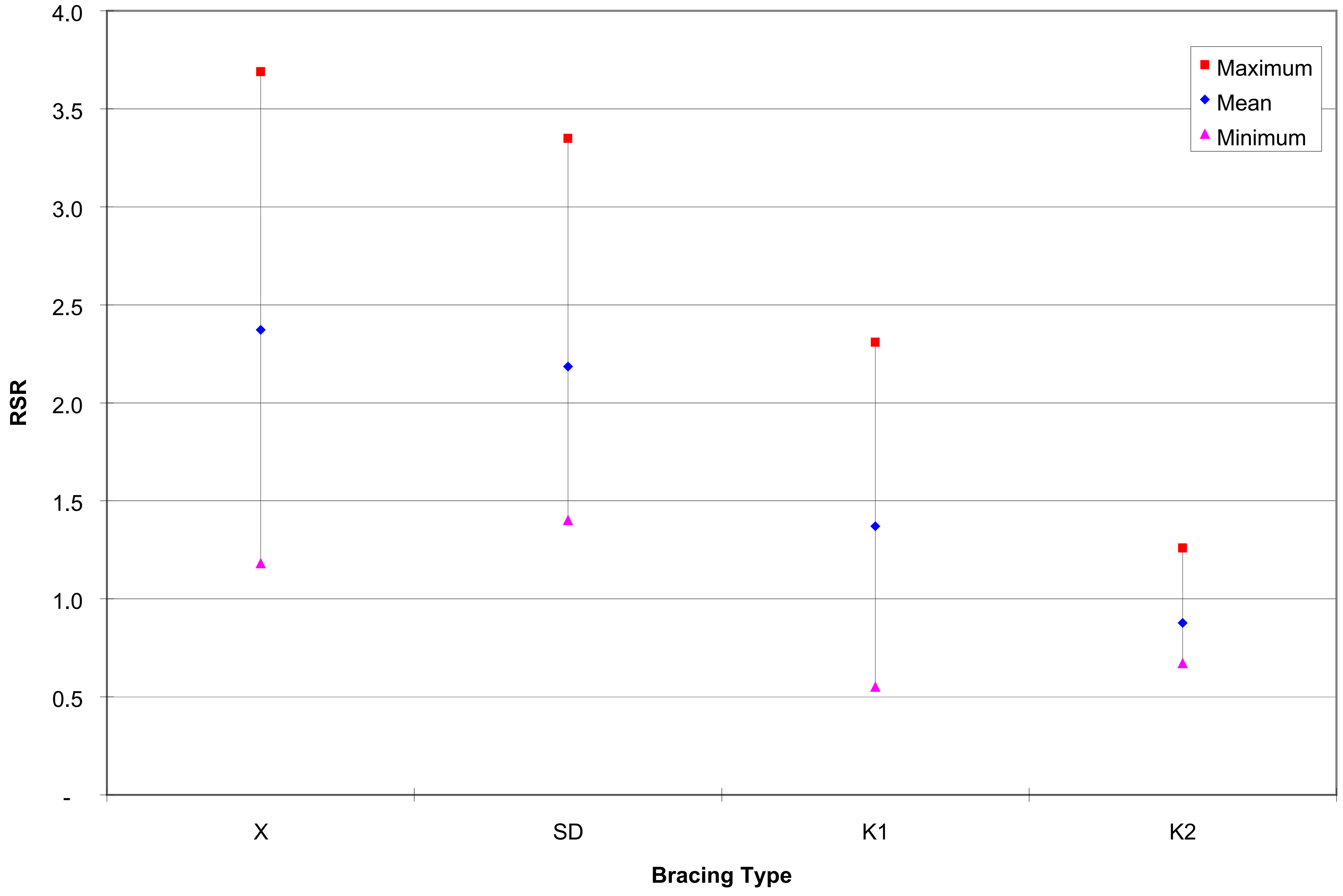


Figure 5.5 (a) Comparison of bracing-schemes four leg platforms (all vintages)

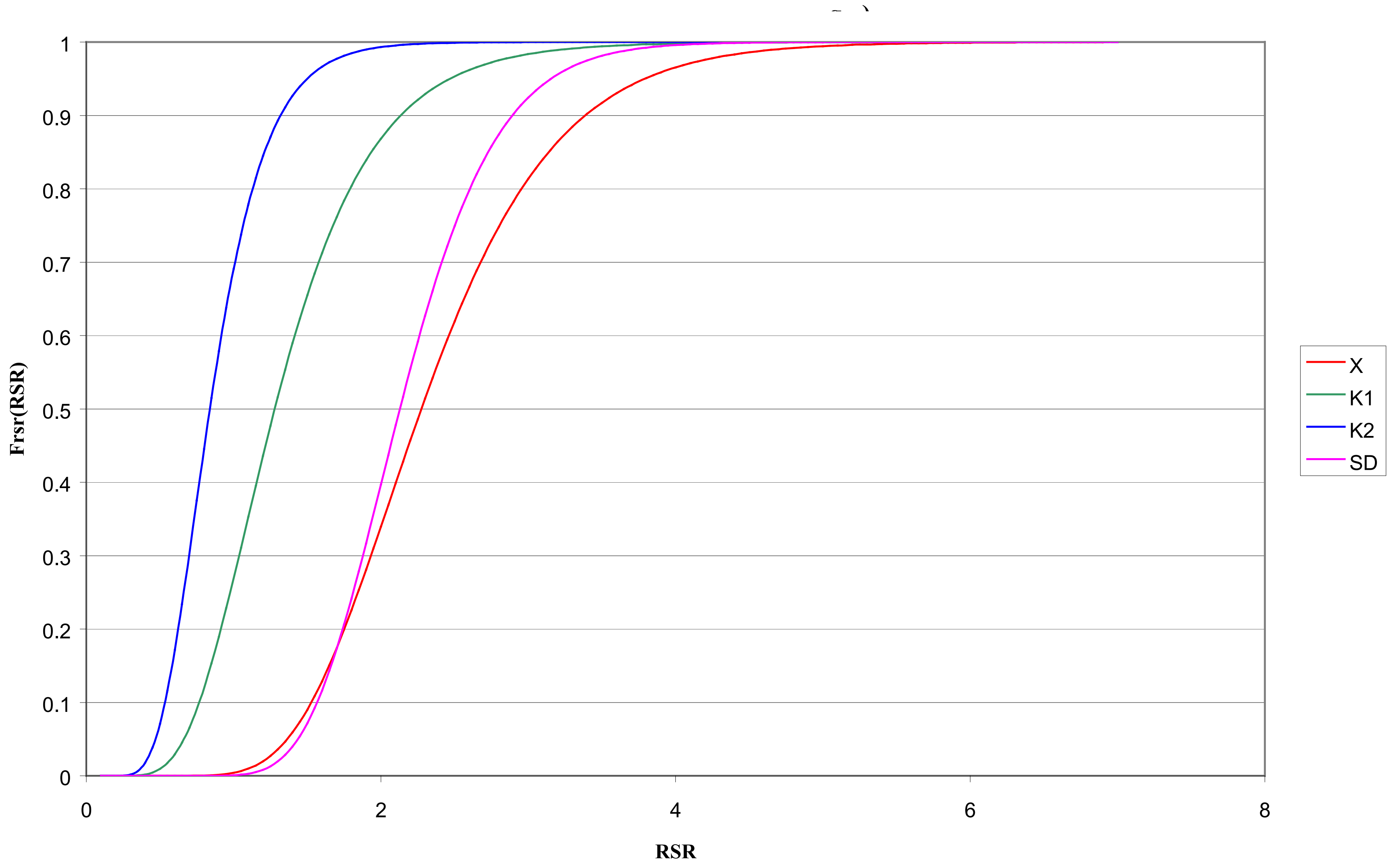


Figure 5.5 (b) Cumulative distribution functions for different bracing schemes four leg platforms (all vintages)

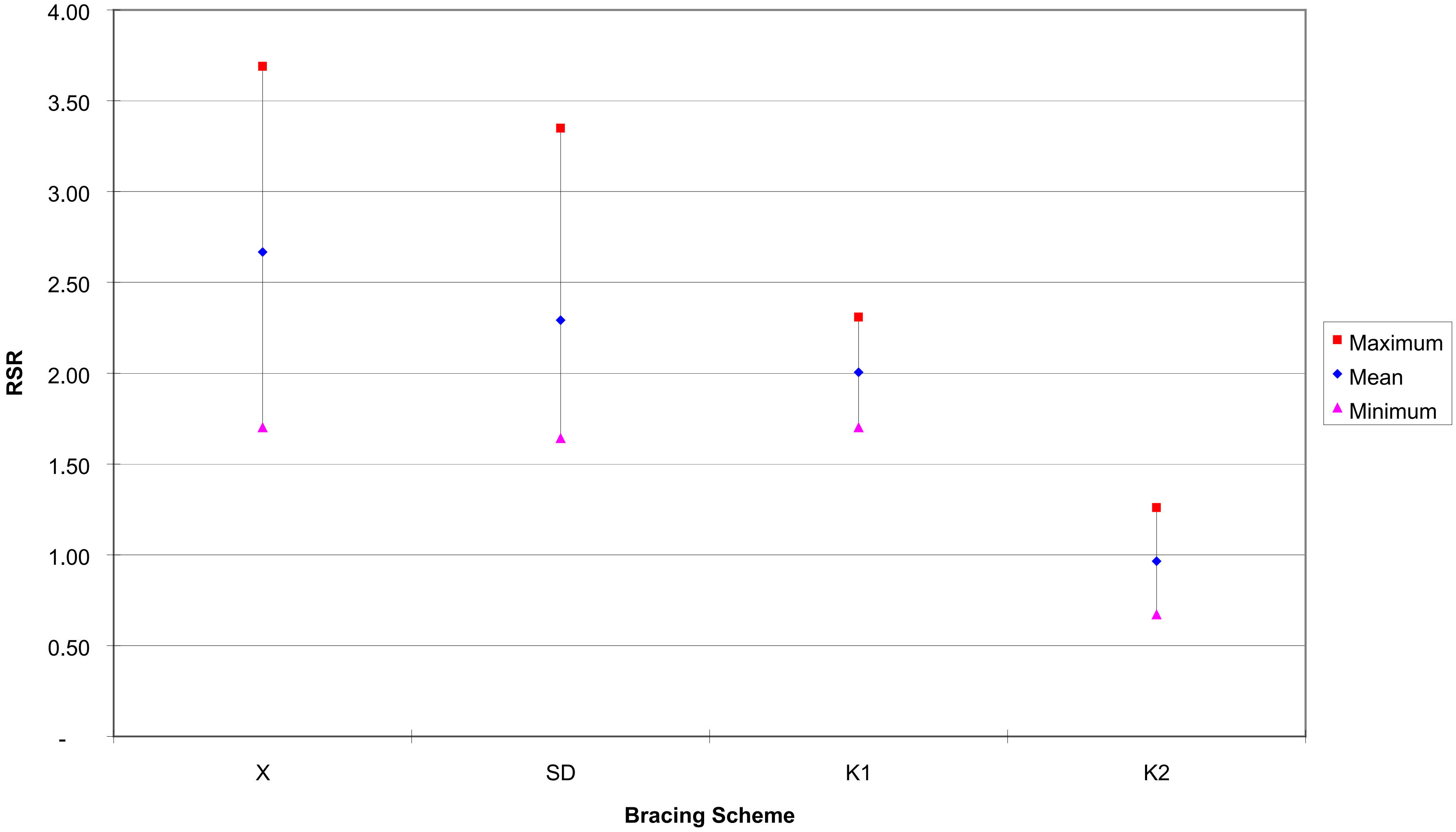


Figure 5.6 (a) Comparison of different bracing schemes (four leg platforms – vintage 1978-1993)

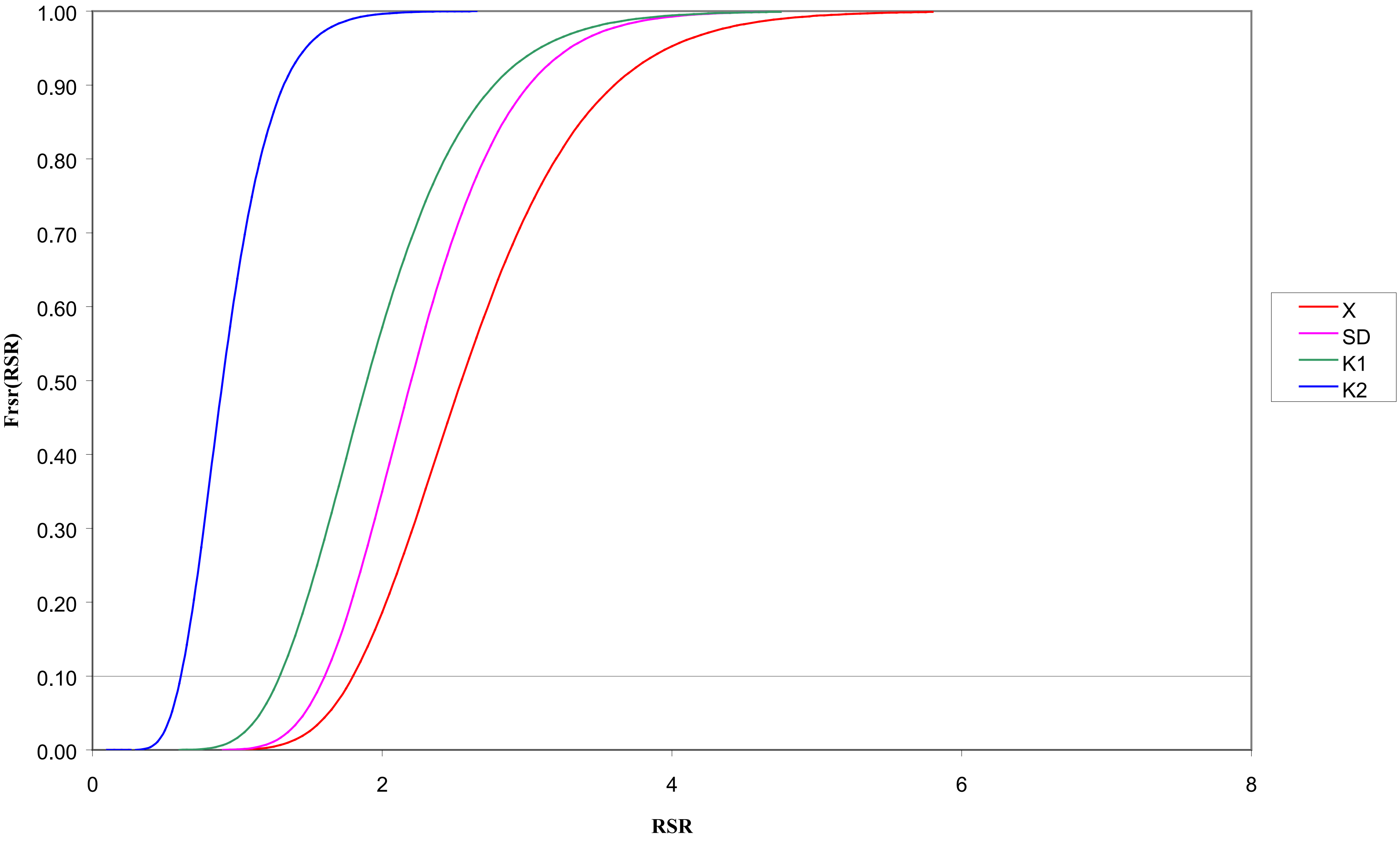


Figure 5.6 (b) Cumulative distribution function for different bracing schemes four leg platforms (vintage 1978-1993)

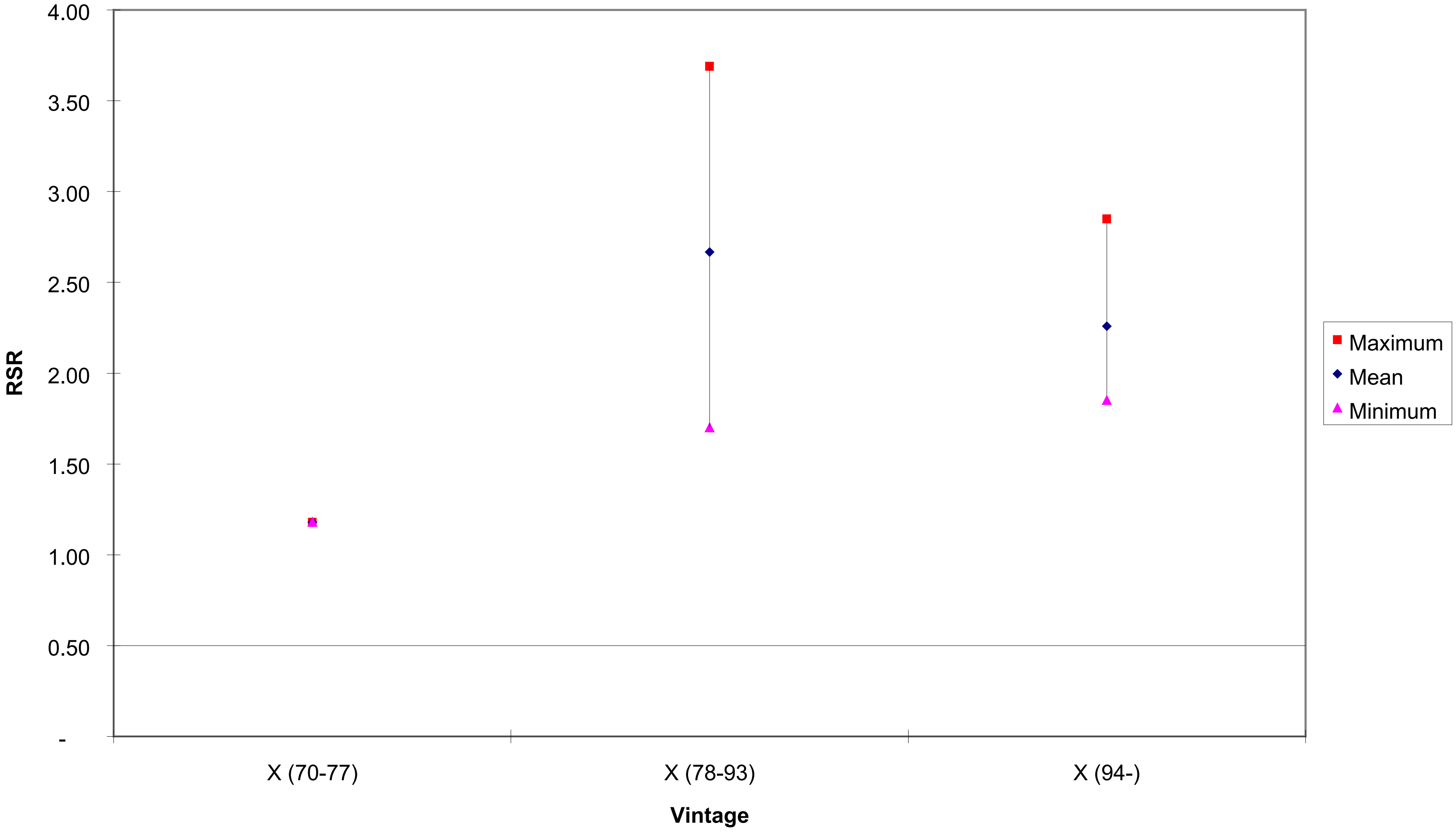


Figure 5.7 (a) Comparison of vintages four leg platforms (X-braced frames)

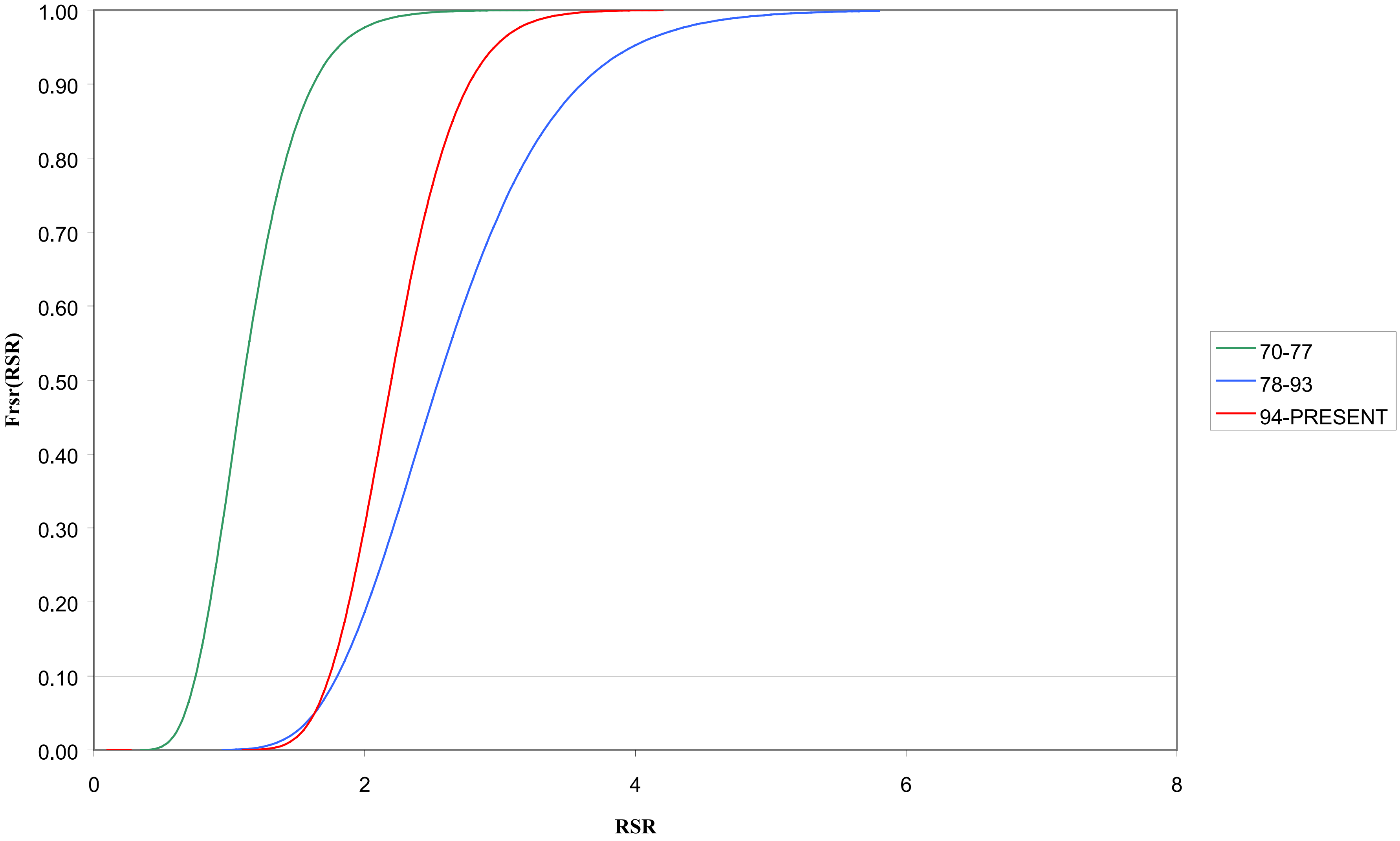


Figure 5.7 (b) Cumulative distribution function for different vintages four leg platforms (X-braced frames)

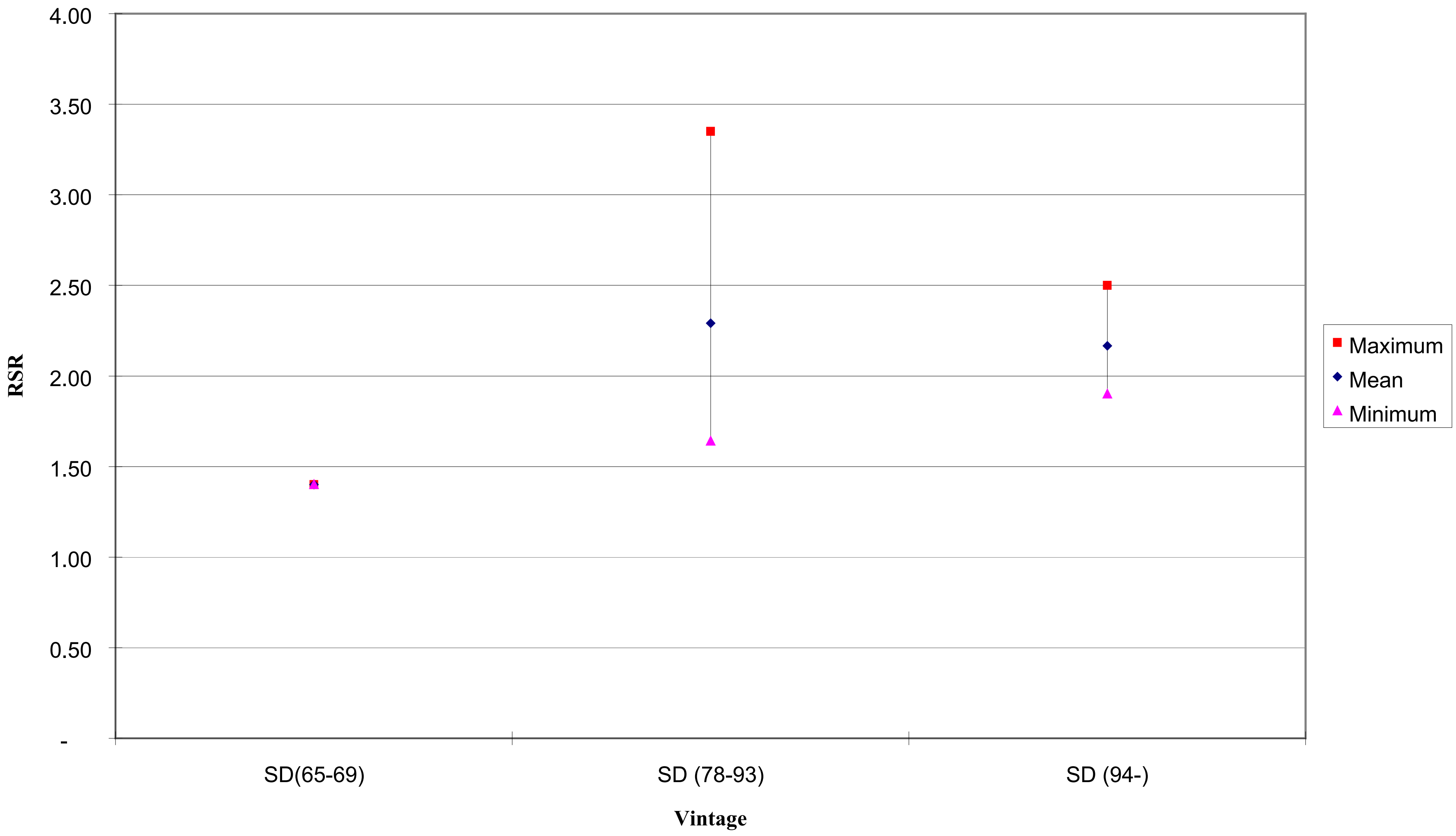


Figure 5.8 (a) Comparison of vintages four leg platforms (SD-braced frames)

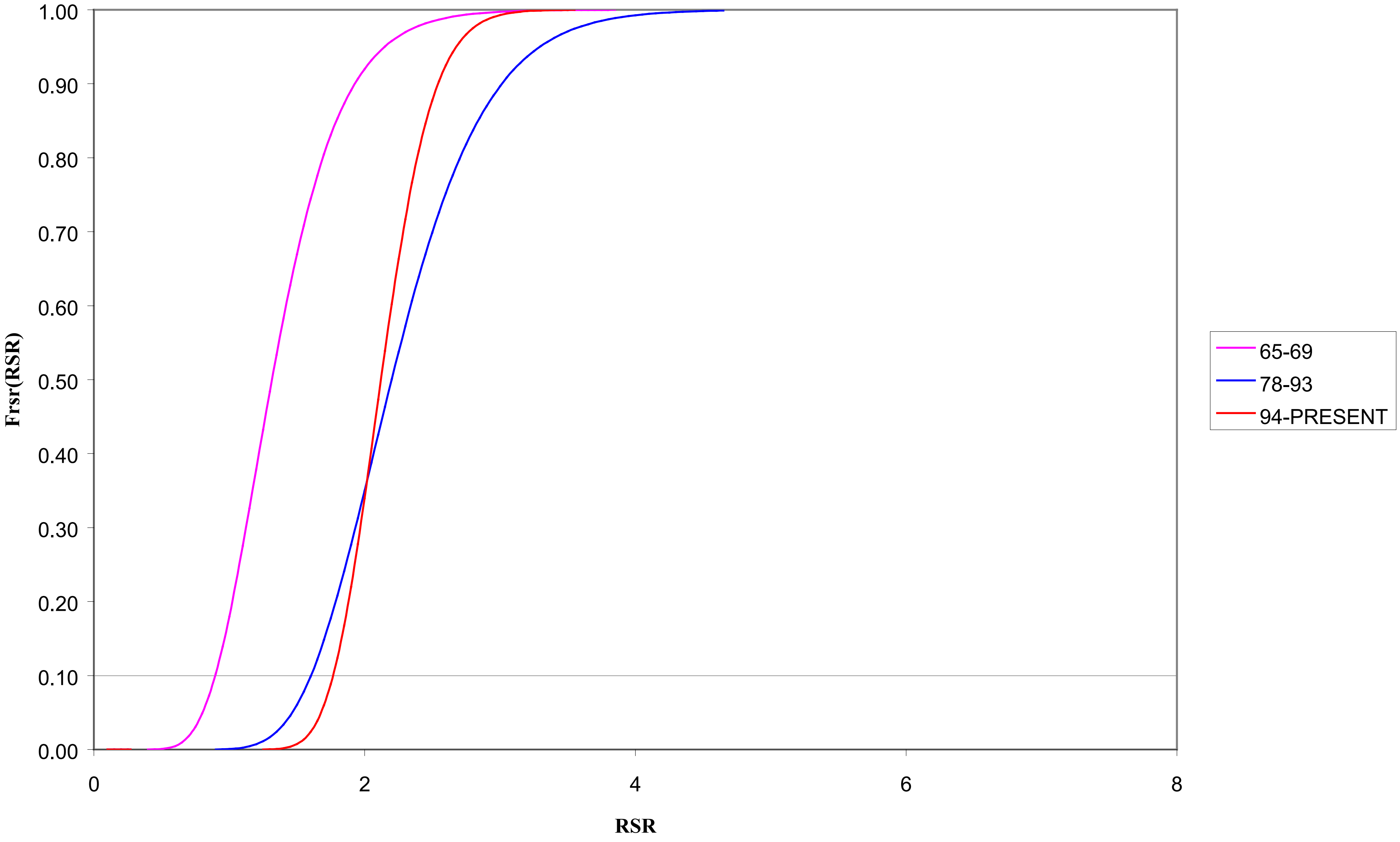


Figure 5.8 (b) Cumulative distribution function for different vintages four leg platforms (SD-braced frames)

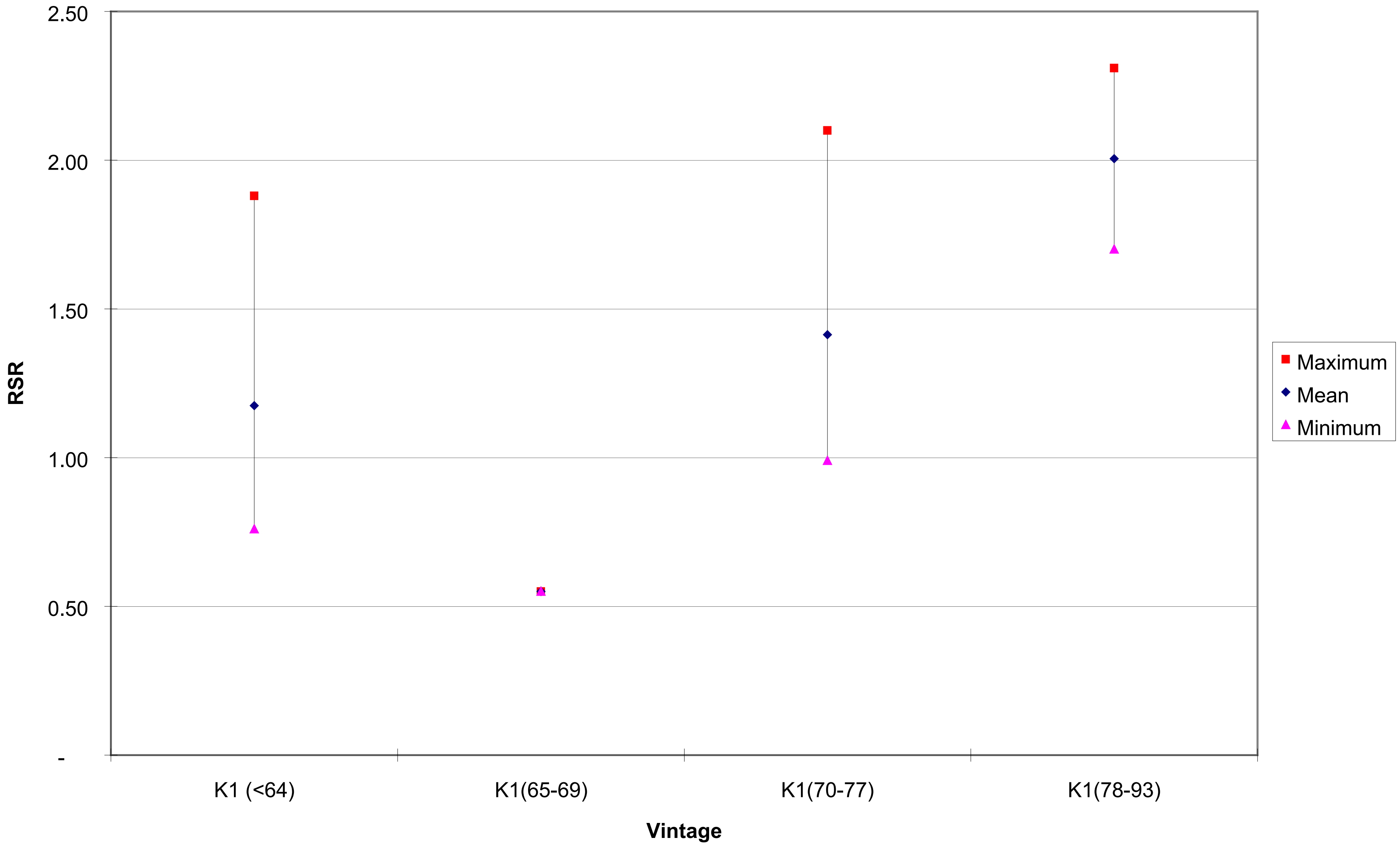


Figure 5.9 (a) Comparison of vintages four leg platforms (K1-braced frame)

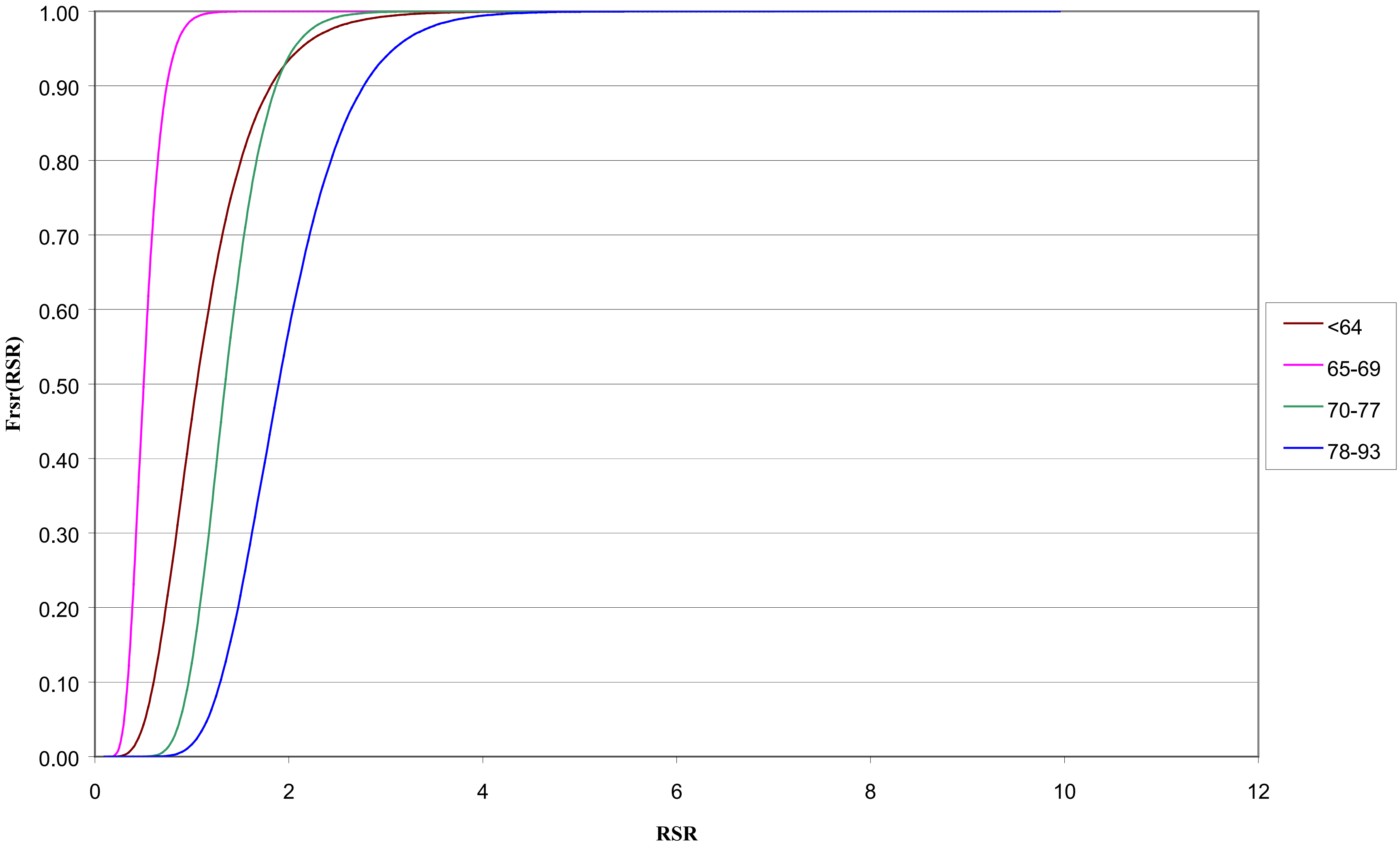


Figure 5.9 (b) Cumulative distribution function for different vintages four leg platforms (K1-braced frames)

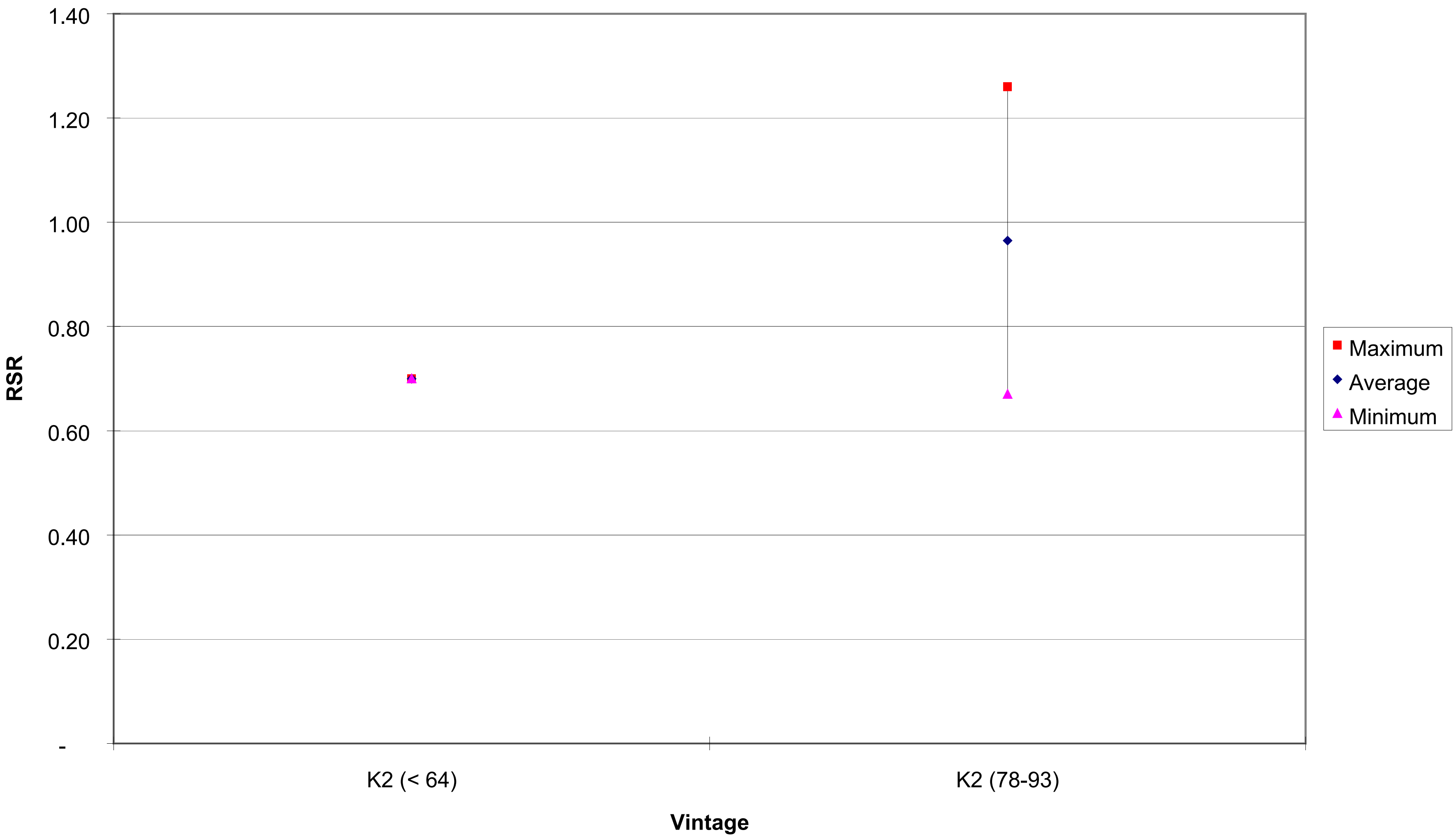


Figure 5.10 (a) Comparison of vintages four leg platforms (K2-braced frames)

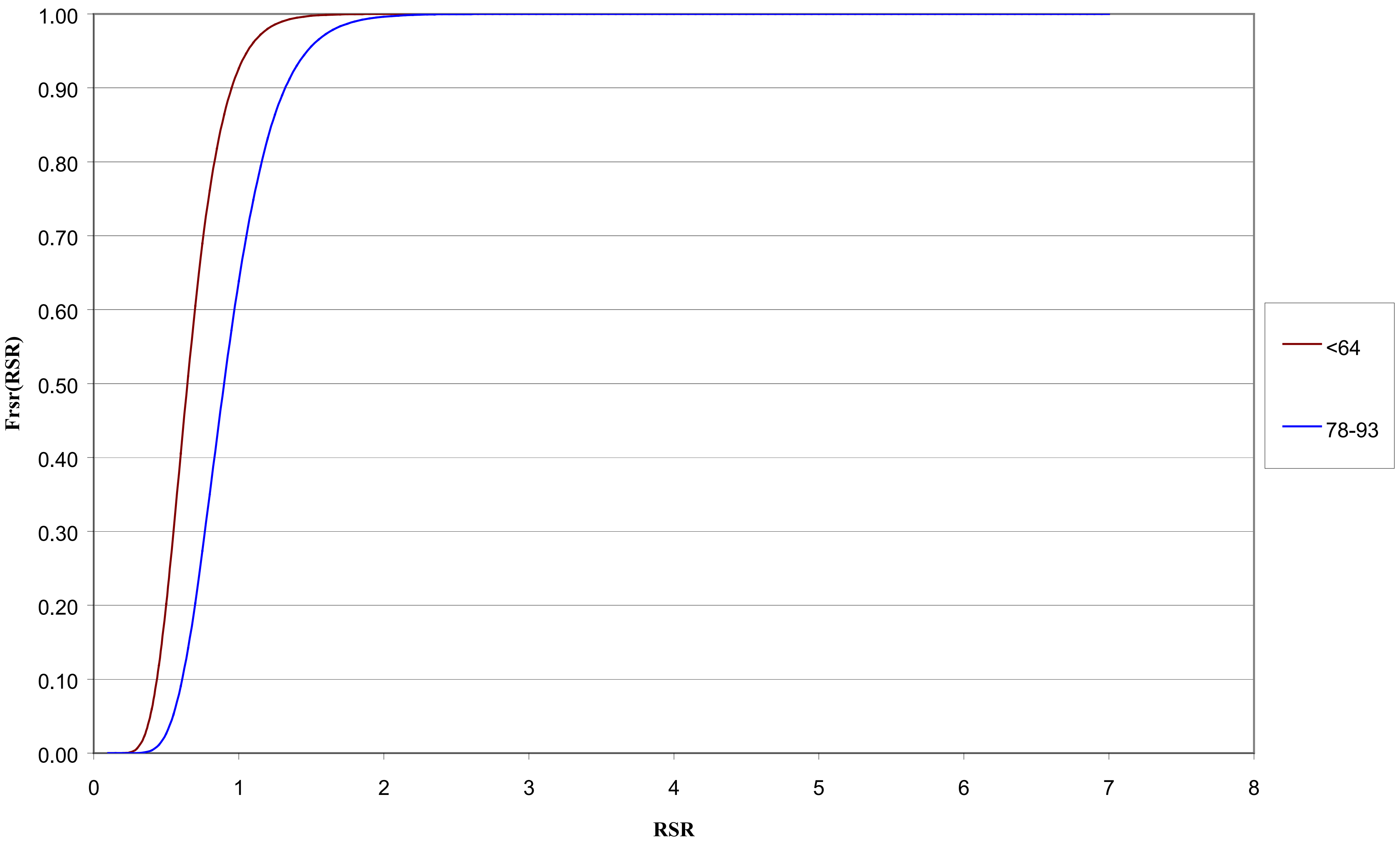


Figure 5.10 (b) Cumulative distribution function for different vintages four leg platforms (K2 bracing scheme)

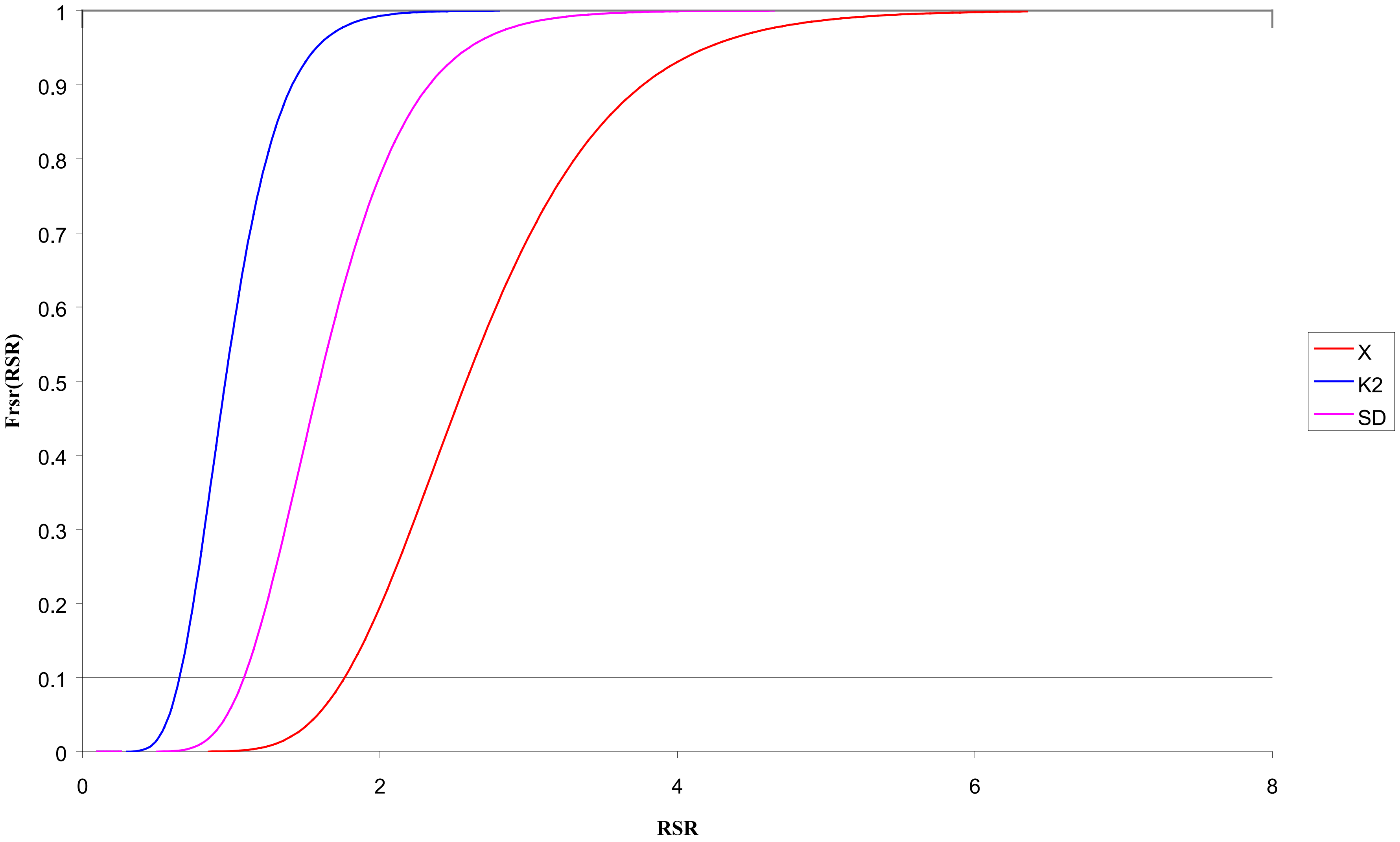


Figure 5.11 Cumulative distribution functions for different bracing schemes six leg platforms

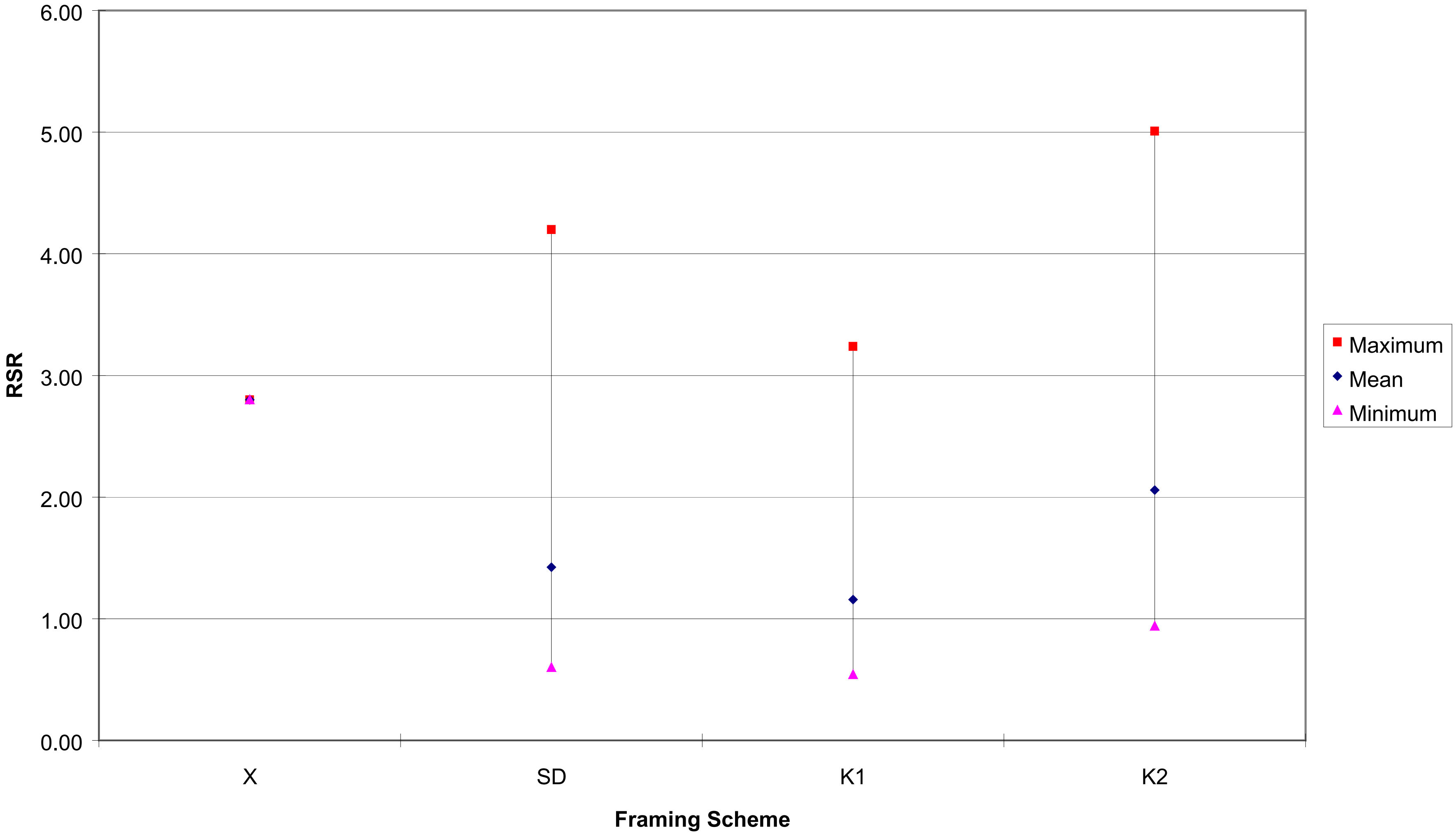


Figure 5.12 (a) Comparison of bracing-schemes eight leg platforms (all vintages)

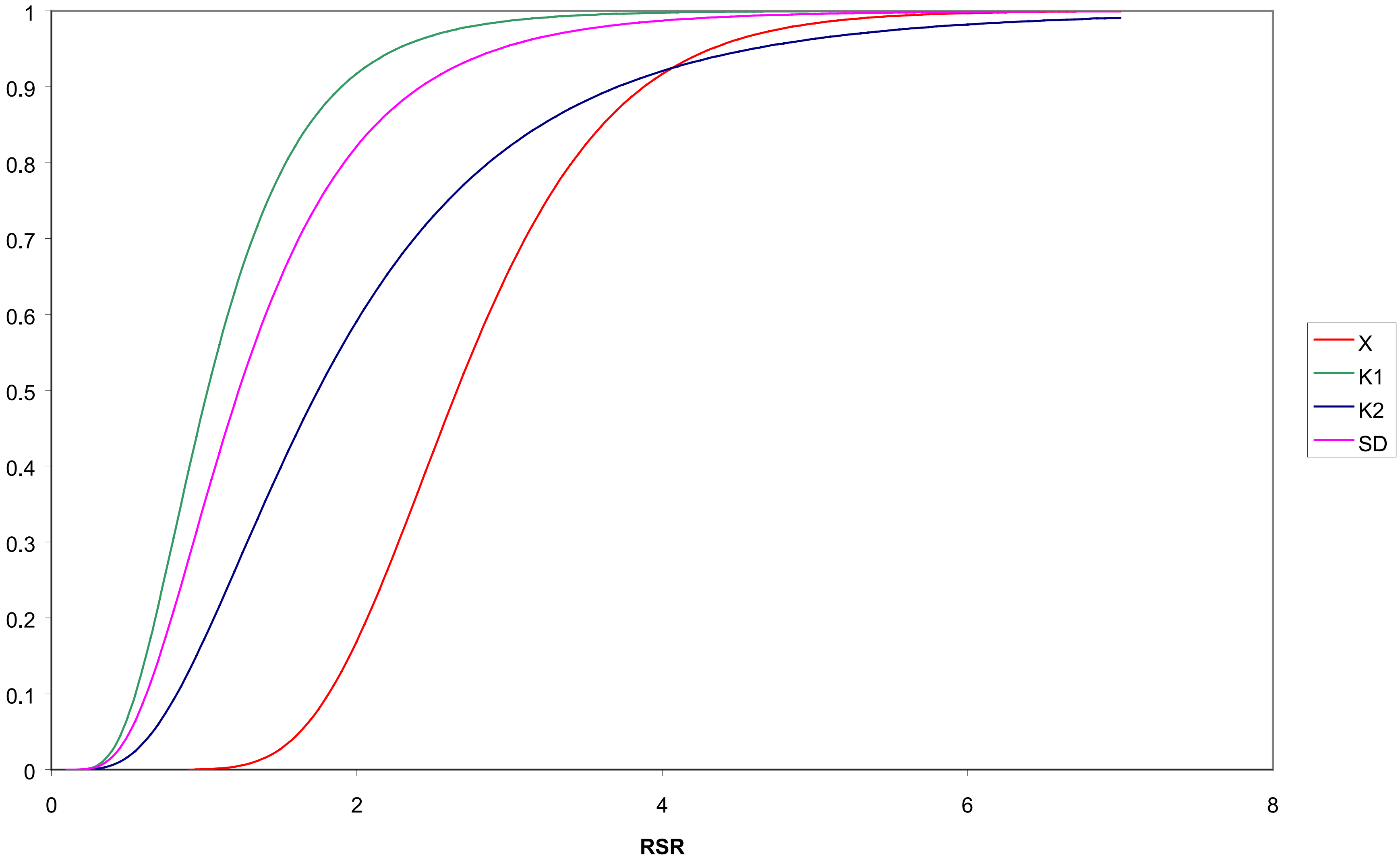


Figure 5.12 (b) Cumulative distribution functions for different bracing schemes eight leg platforms (all vintages)

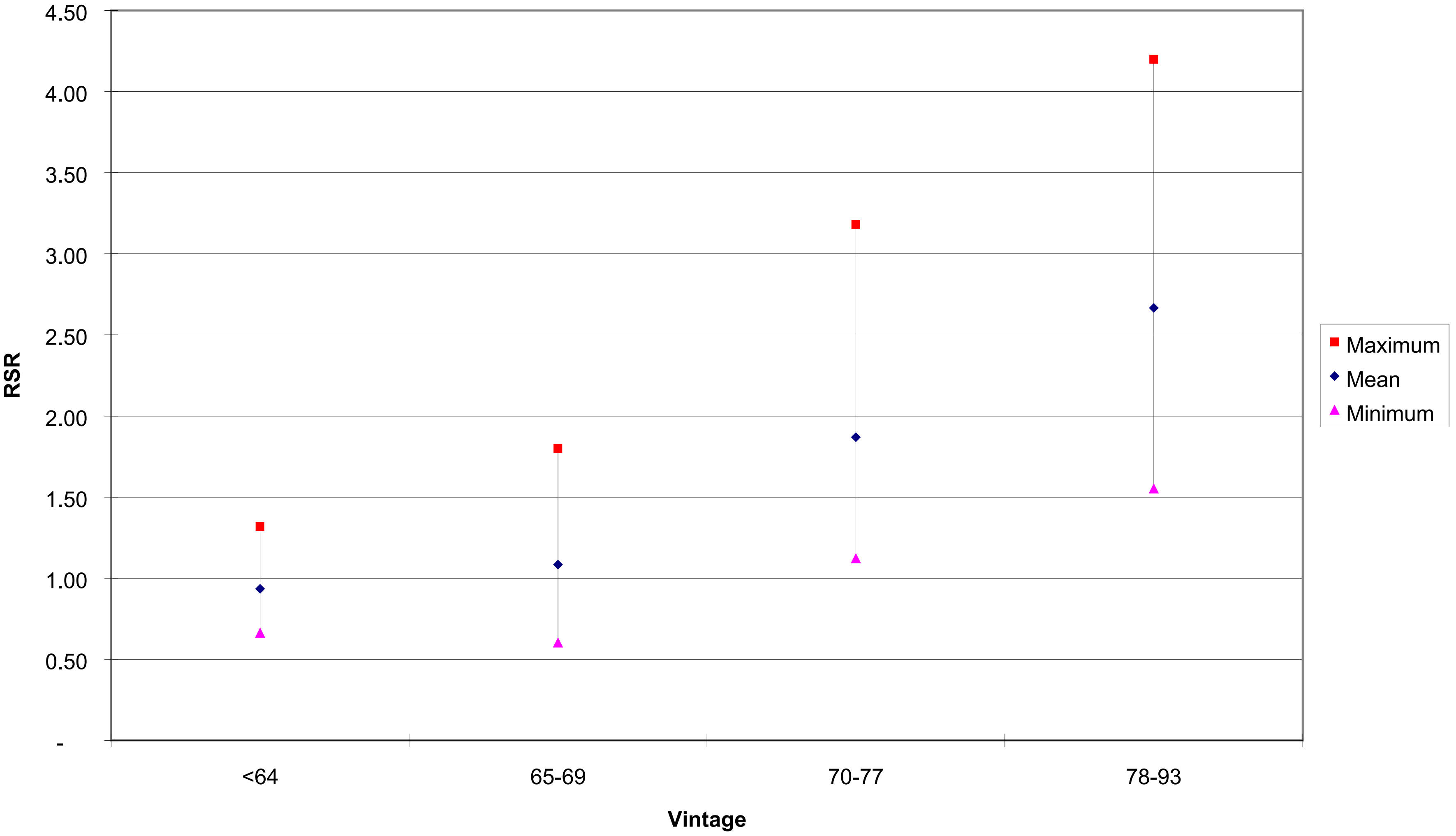


Figure 5.13 (a) Comparison of different vintages eight leg platforms (SD-braced frames)

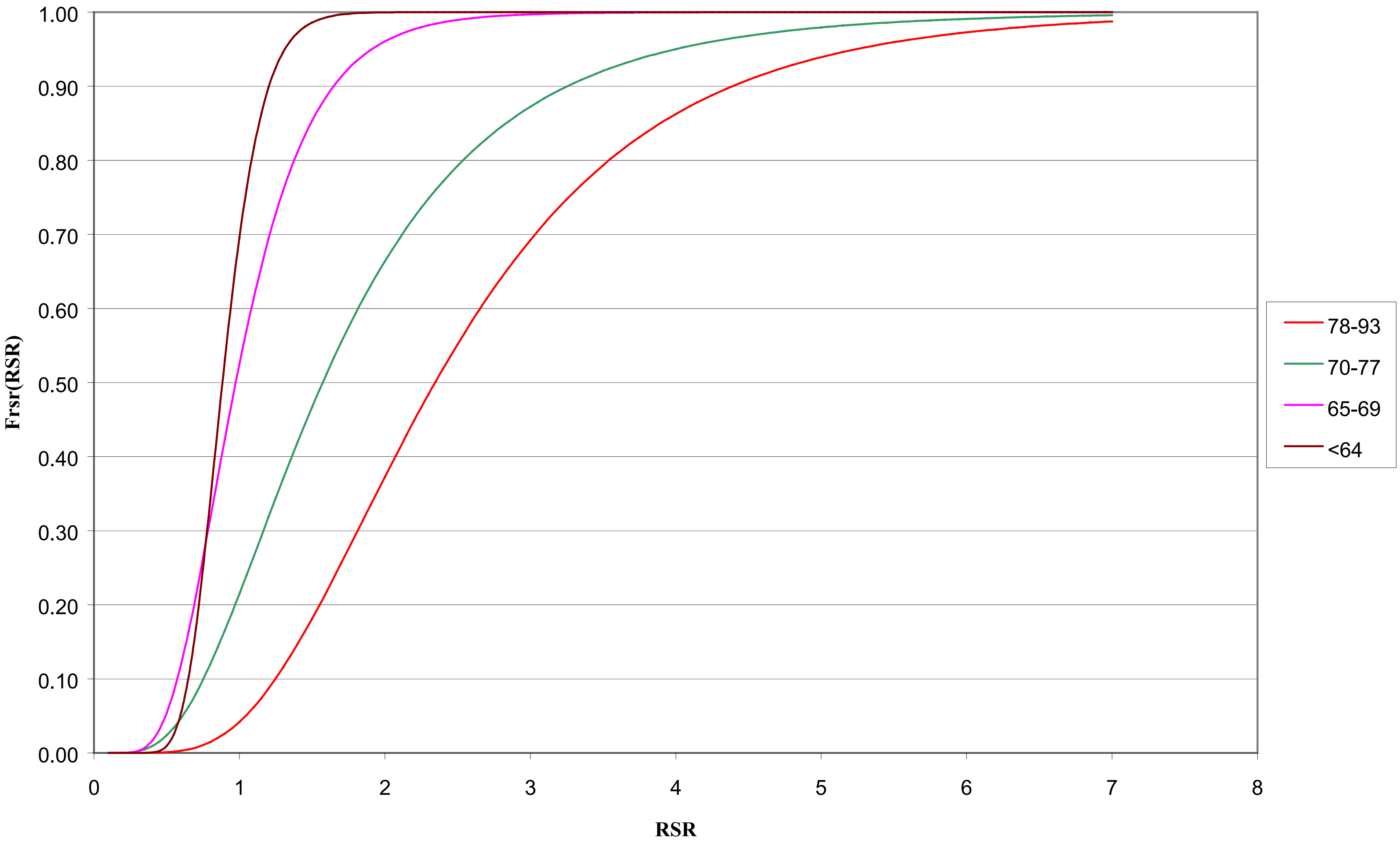


Figure 5.13 (b) Cumulative distribution functions for different vintages eight leg platforms (SD-braced frames)

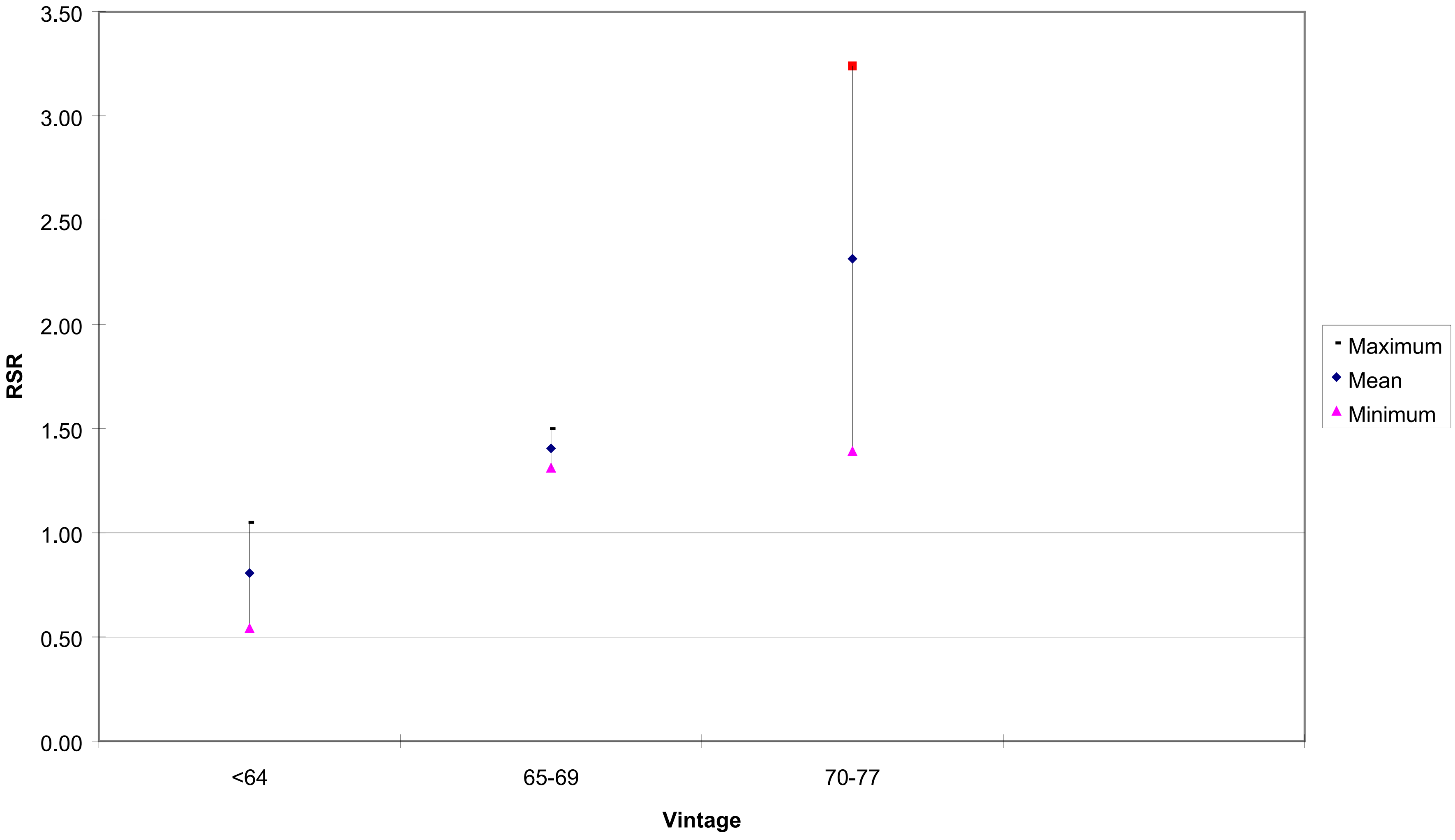


Figure 5.14 (a) Comparison of vintage eight leg platforms (K1-braced frames)

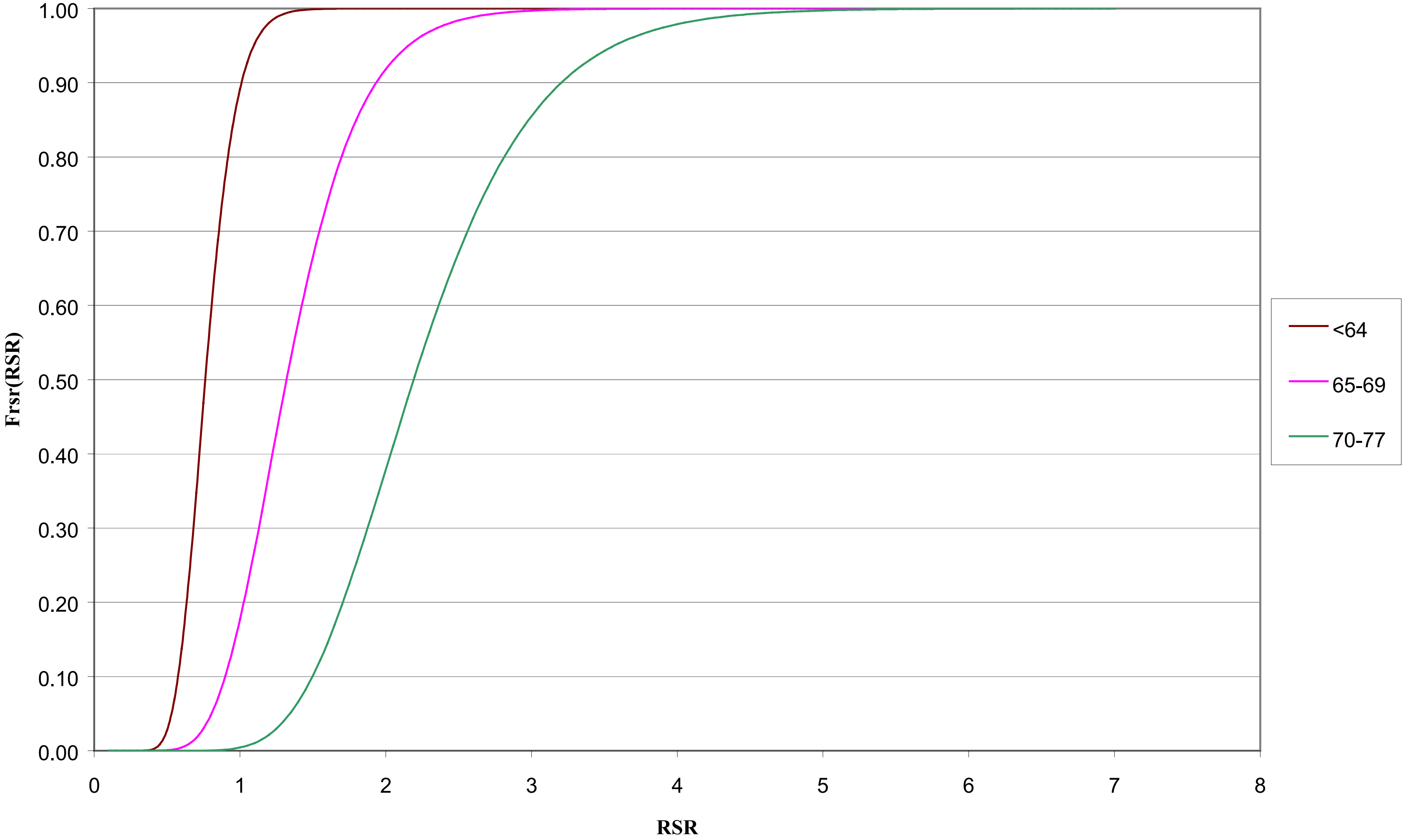


Figure 5.14 (b) Cumulative distribution functions for different vintages eight leg platforms (K1-braced frame)

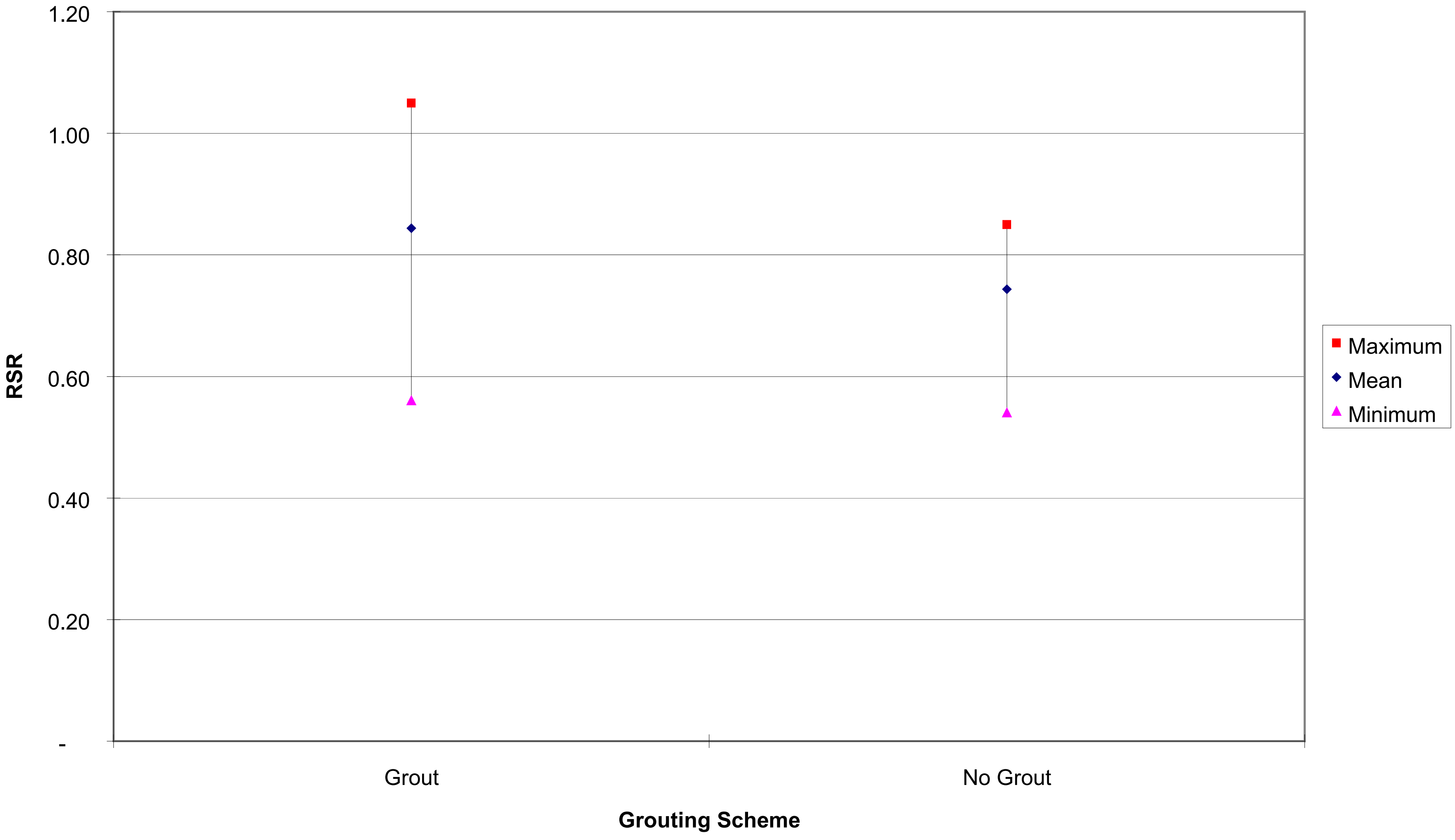


Figure 5.15 (a) Comparison of leg/pile anuulus grout eight leg platforms (K1-braced frames, vintage <1964)

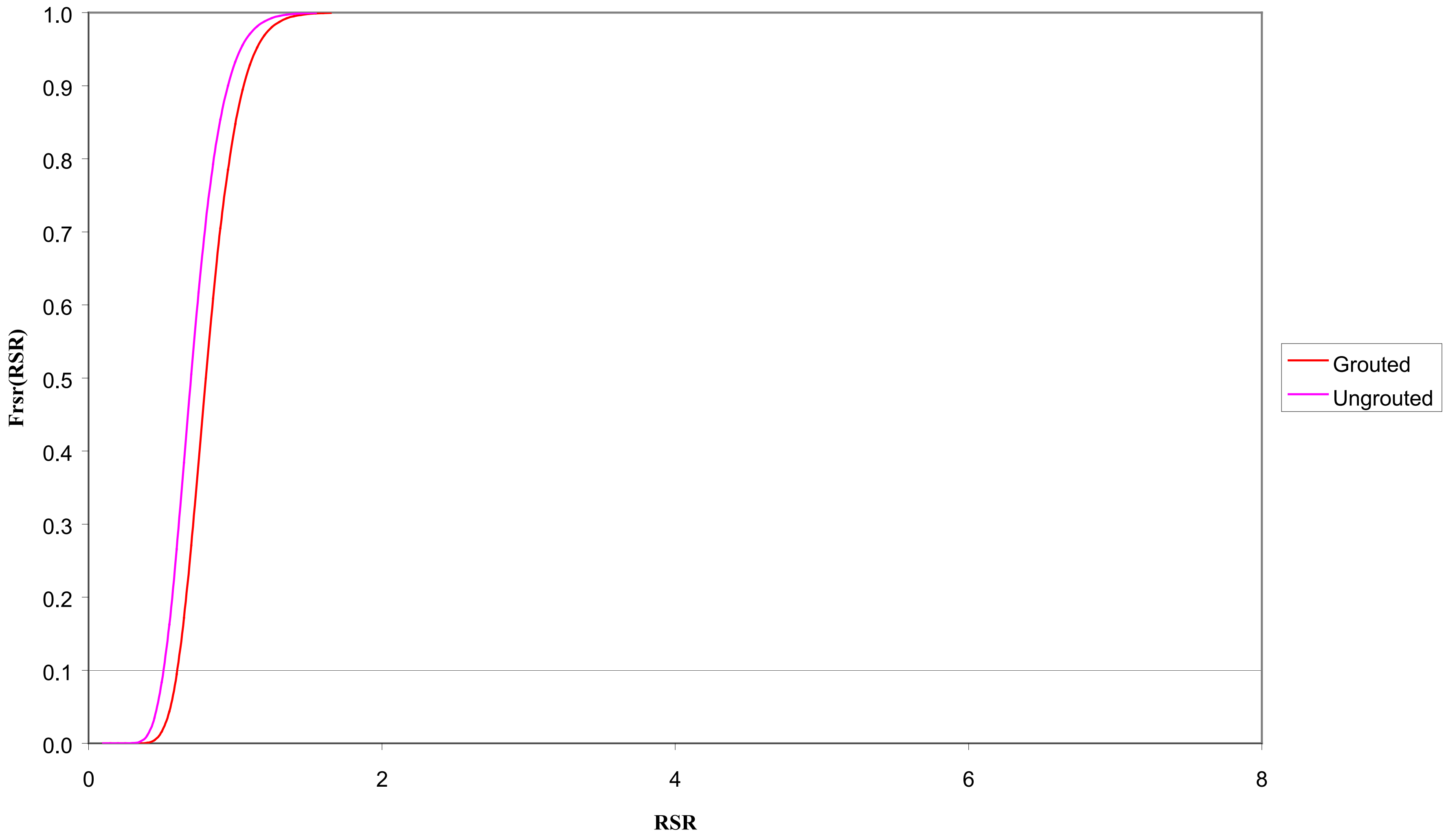


Figure 5.15 (b) Cumulative distribution functions for leg/pile annulus grout eight leg platforms (K1-braced frames, vintage <1964)

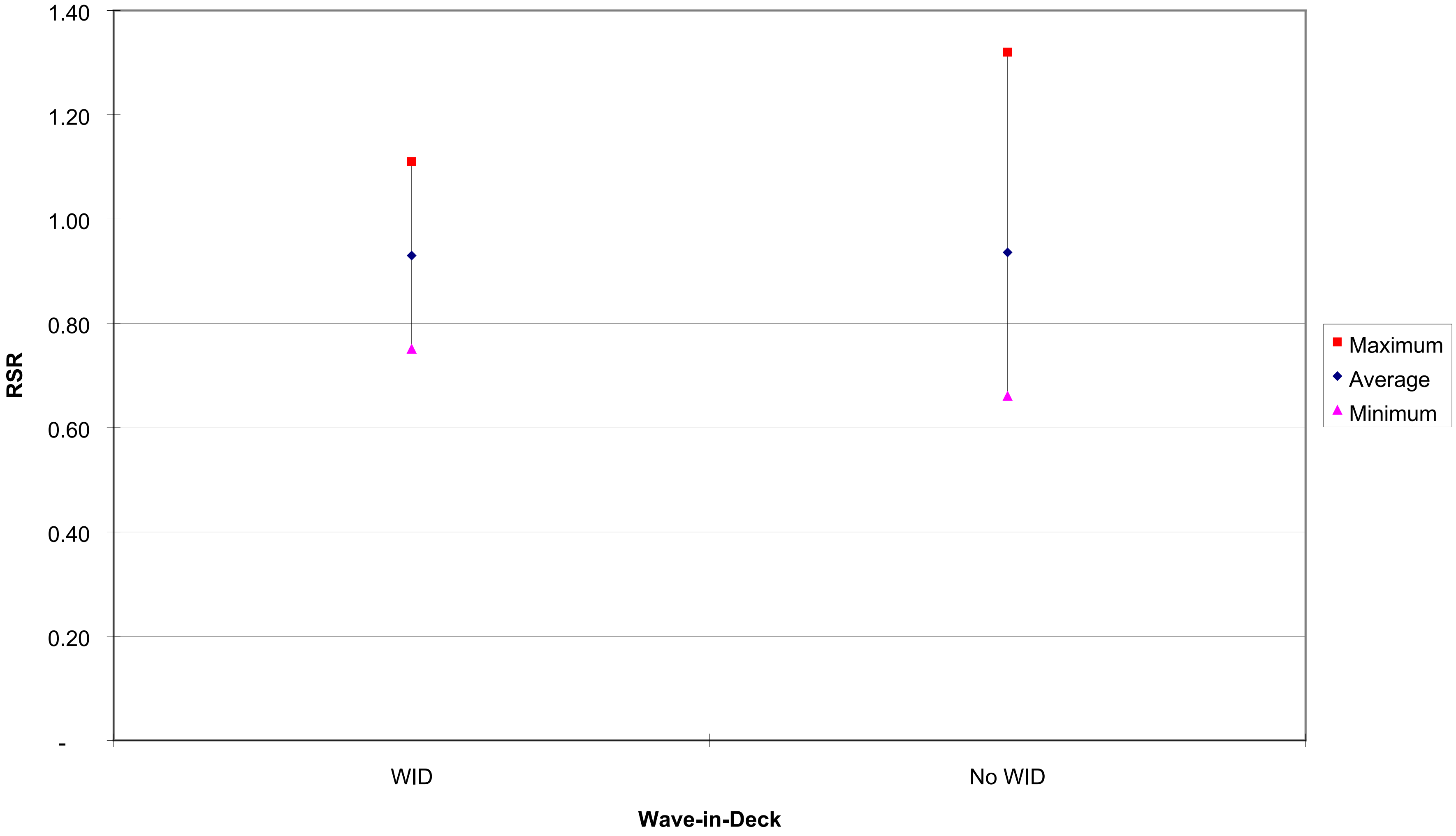


Figure 5.16 (a) Effect of wave in deck eight leg platforms (SD-braced platforms, vintage <1964)

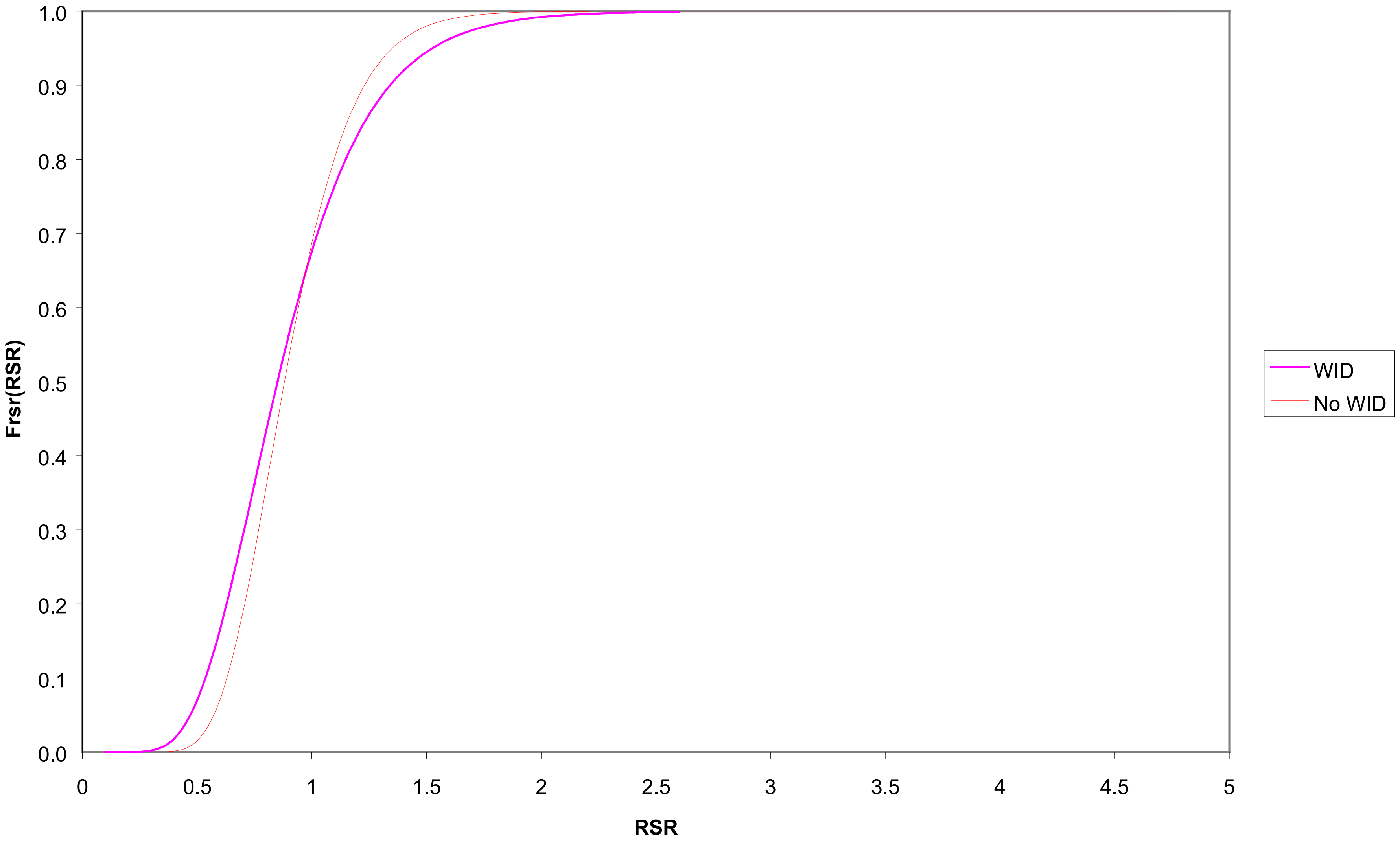


Figure 5.16 (b) Cumulative distribution functions for effect of wave in deck eight leg platforms (SD-braced platforms, vintage <1964)

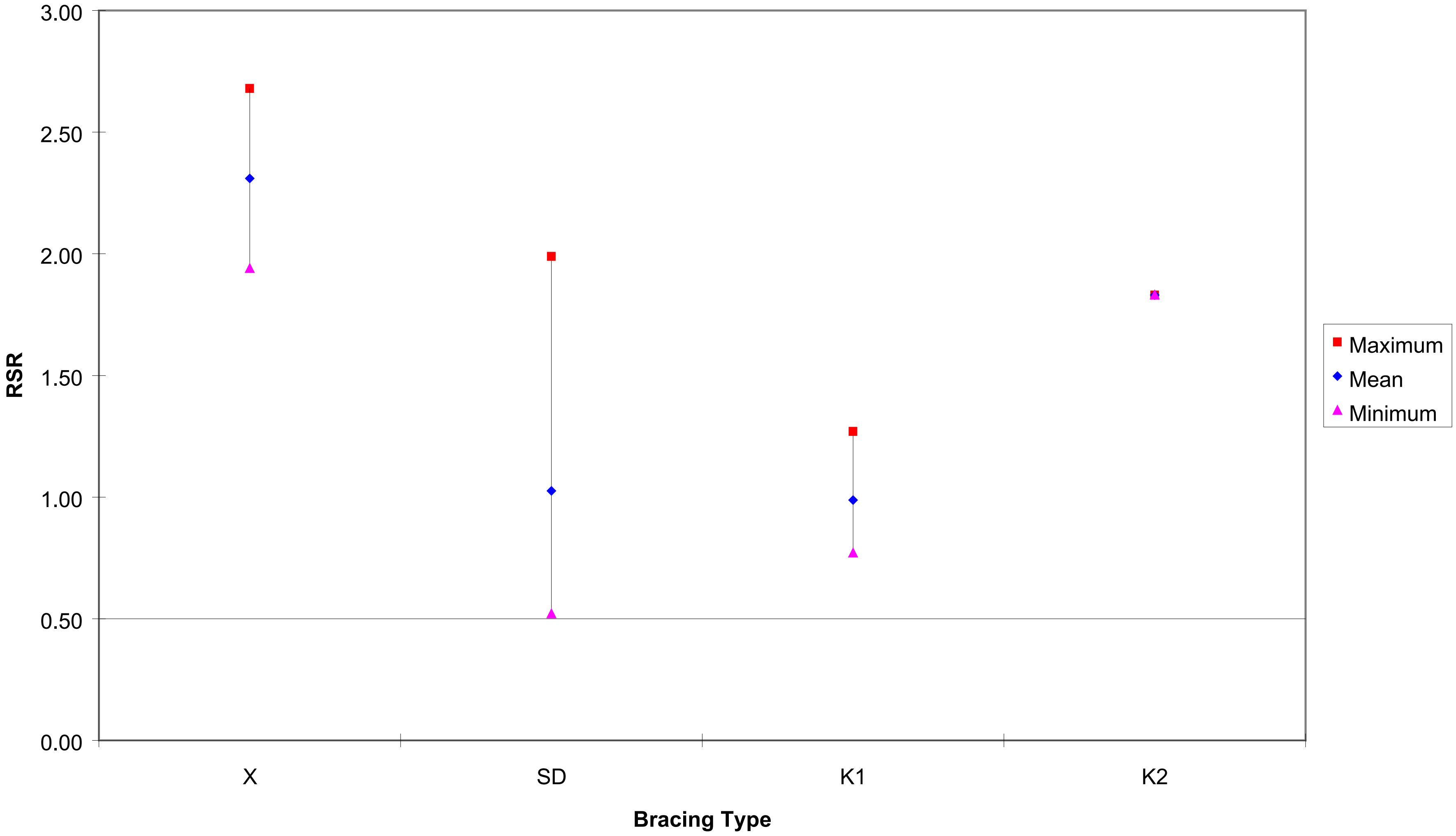


Figure 5.17 (a) Comparison of bracing-schemes platforms with more than eight legs (all vintages)

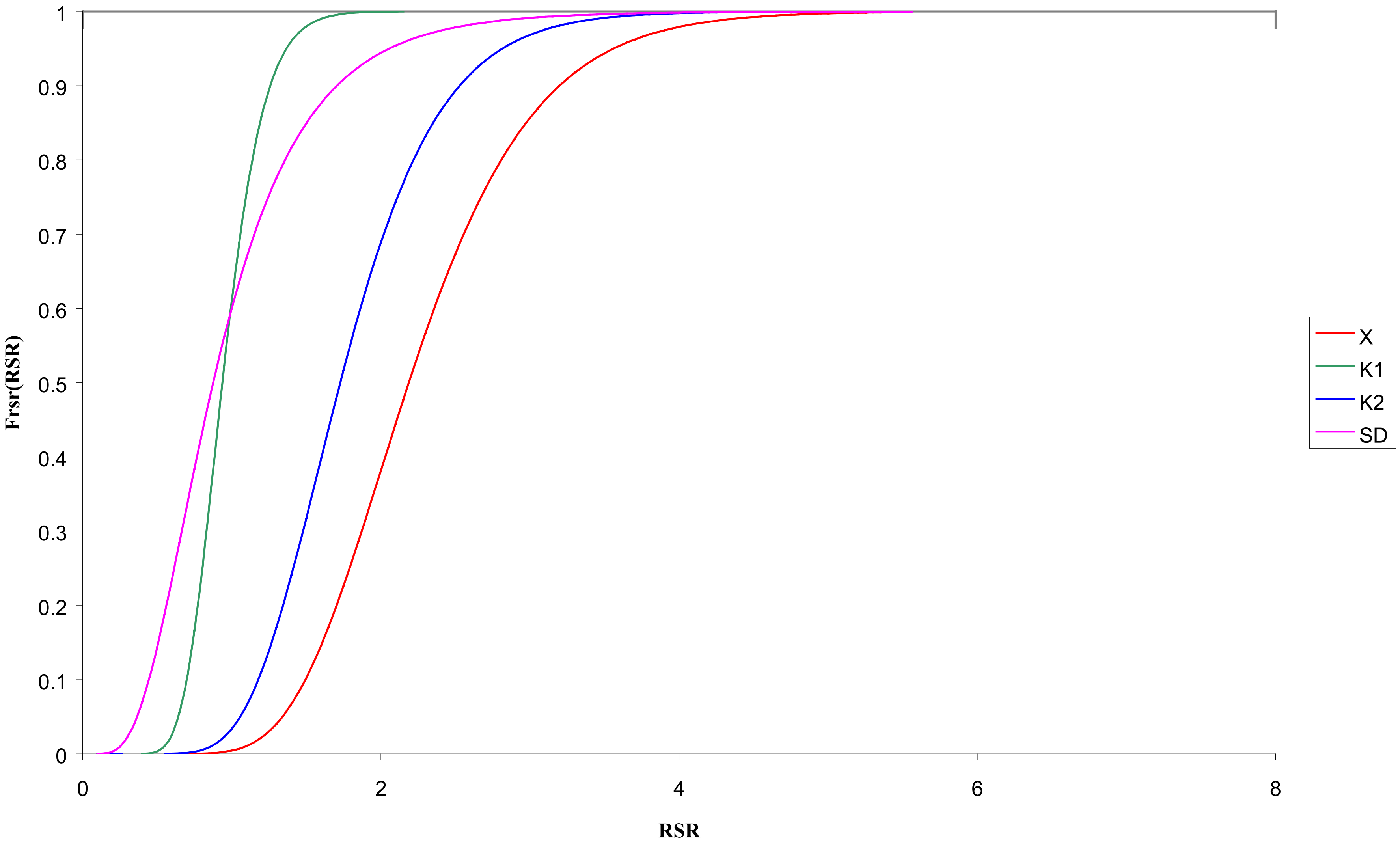


Figure 5.17 (b) Cumulative distribution functions for platforms with more than eight legs

6.0 INSPECTION PLANNING

Underwater inspection, along with structural assessment and data management, are an integral part of structural integrity management of an offshore platform. During the lifetime of an offshore structure, it may be exposed to a number of hazards including extreme storms, seismic loads, ship impact, dropped objects, degradation due to fatigue, corrosion, and fracture. The purpose of inspection is to reveal possible deterioration and damage caused by these events. The significant costs of the underwater inspection make it important to prioritize and limit inspections, thus making the development of an effective inspection plan and strategy essential.

The damage tolerance of a platform plays an important role in determining its risk. As defined in previous sections, robustness is a measure of the damage tolerance – the more robust, the more that a platform is tolerant to damage. Thus, robust structures may not need as much inspection as other structures, thus allocating inspection resources to platforms with higher risk.

The issues addressed in this project, such as number of legs, bracing schemes, etc., are representative of the structure configuration only and reflect the *likelihood of failure*. Inspections should also consider the use of the structure (drilling, production, quarters, central hub platform) and the associated *consequence of failure.* For example, an unmanned wellhead platform versus a manned production platform. It is more critical to ensure integrity of the manned facility and as such, in some cases, it would receive priority for inspection. A true "risk based" platform inspection planning process considers both the likelihood of failure and the consequence of failure. EQE worked with BP Amoco to develop such an approach as described in Reference 12.

While developing a complete inspection plan based on the robustness is not within the scope of this study, the influence of the key factors studied in this project can help focus inspections to the most critical platforms and the most critical areas of these platforms. Further work is needed, as explained in Section 7, to fully develop a true risk based inspection plan. However, several of the key findings of can be used to help develop inspection plans. These are summarized as follows:

- *Number of legs*: Eight- and six- leg platforms are more redundant than four- and three leg platforms, and therefore more damage tolerant. This was shown in numerous evaluations of the dataset. While preparing an inspection plan, eight- and six-leg platforms can be considered more robust, thereby prioritizing the inspections on four- and three-leg platforms. However, this must be combined with the platform bracing scheme and vintage as described below. For example, a newer 4 leg, X braced platform may have more robustness than an older 8 leg K braced platform.

- *Bracing scheme*: The 2D ultimate strength analyses described in Section 4 clearly demonstrated that X-braced frames are more robust than the K- and diagonal-braced frames due to the availability of alternate load paths. This robustness of X bracing was also shown in the statistical comparisons of the dataset. The advantages of robustness of an X-braced frame should be considered when developing the inspection strategy. This includes extending the interval of periodic underwater inspections or demonstrating that an immediate repair is not essential in the event of damage being found.

  Gebara et al. [2] further highlight the advantages of X-braced structures some of which include, ease of fabrications, capability of X-braced structure to redistribute load without a sudden drop in strength, and the capability of X-braced structures to sustain damage with a smaller increase in probability of failure compared to other framing patterns.

It should be noted that the horizontal braces in the vertical frames are relatively less important in X-braced frames than in other braced frames. Table 4.3 in Section 4, shows that when the horizontals of an X-braced frame are damaged, there is 3% reduction in RSR compared to a 50-65% decrease for the other framing schemes, with the K-bracing schemes having the largest reductions. Hence, while inspecting the horizontals in X-braced structures may not be crucial, it might be vital to inspect the horizontals in other framed structures

- *Vintage*: As shown by evaluation of the dataset, the performance of platforms improves in platforms of more recent. The vintage of the platform reflects the platform characteristics as design practices have evolved over the time. Newer platforms are designed to better standards and practices (joint cans, higher deck height/air gap, overlap of joints, etc.) and hence more robust than older platforms. Thus, older platforms in the same fleet should have a higher focus for inspection. However, if the previous inspections reveal that a newer platform has a track record of damage such as fatigue cracking in the conductor bays, perhaps because of same initial design or fabrication flaw, this particular platform will require additional and more regular inspection (see last bullet item below).

- *Leg/Pile grouting*: As discussed in Section 3 and the dataset evaluation in Section 5, grouting of the leg/pile annulus increases the capacity of the joints of the braces framing into the leg and thus increases the overall strength of the platforms. Platforms without leg grouting may be more susceptible to joint damage, which can decrease platform capacity.

Wave-in-deck and other design defects or platform damage: Some older platforms have low-set decks that may be impacted by design waves. There were several platforms of this type in the dataset and these platforms clearly showed lower ultimate strength and RSRs compared to platforms with higher decks. This type of problem can be considered a “design flaw.” Likewise, other platform may have a fabrication/installation defect such as a dent or crack. Platforms with these characteristics will likely have lower ultimate strength and RSRs than similar undamaged platforms, and may require more focus for inspection.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 TWO-DIMENSIONAL FRAME ANALYSES

The pushover analyses of the 2D damaged and undamaged frames illustrates the advantages of X-bracing over K-bracing and diagonal bracing. X-bracing offers redundancy and alternate load paths to resist the loading once the compression brace buckles, that enhances the overall platform system strength. This was shown by the comparison of the RRF (Residual Resistance Factor, computed as damaged capacity divided by undamaged capacity) for each of the bracing schemes. The lowest RRF for the X-braced structure was about 50%, whereas the diagonal and K-braced structures had RRFs in the range of 15%. This clearly demonstrates that platforms based upon X-braced schemes have "significant" more reserve capacity in the damaged state than platforms with the other bracing schemes –perhaps as much as 2-3 times.

This work also developed a ranking of platform members in terms of robustness. This "member importance" can be used as a general guideline for identifying critical members for inspection on platforms of different framing schemes. However, as pointed out in Section 6, there are many factors involved in inspection planning, such as 3-D effects, member sizing, consequence of failure of the platform and existing damages that should be taken into account in any inspection program. Therefore, this information should always be used in combination with other pertinent data.

7.2 DATASET EVALUATION

A dataset was developed in Excel spreadsheet format of the platform information and analyses results for 65 platforms and 190 individual pushover ultimate strength analyses. This data was then evaluated for trends and other characteristics that may be useful in understanding the performance of platforms at ultimate capacity and for inspection planning. Several of the key findings are as follows:

- = *Platform vintage*. Newer platforms perform better than older platforms. This is an expected result given the advances in design codes and was confirmed by this study.
- *Number of legs*. The more legs the better in terms of reserve strength ratio (RSR). While RSR is not an explicit measure of robustness (in terms of damage tolerance), a higher RSR does indicate a lower reduction in capacity given the loss or damage to any one platform member.
- *Framing scheme*. The dataset evaluation showed similar results as the 2D analysis in terms of framing, with the X braced framing in the dataset of 3D platforms analyses also performing the best.
- *Other issues*. Grouting of the leg-pile annulus (which increases platform capacity, particularly joints) and situations where the design wave impacts the deck (older platforms with low set decks, which decreases capacity) were shown to be other issues where there was a consistent trend.

This information is also useful for inspection planning, particularly for determining the priority for inspecting specific platforms in a fleet. For example, older platforms with K or single diagonal framing that are susceptible to wave-in-deck loading during the design event are of higher priority than new platforms of X braced design.

7.3 RECOMMENDED ADDITIONAL WORK

This project has provided an opportunity to put together the various pushover analyses performed in the past and study the effect of different parameters on the ultimate strength of the platforms. In addition, the effect of bracing schemes on strength and robustness was studied quantitatively by conducting pushover analyses of 2D frames with different bracing schemes. The following recommendations are made to extend this information and to develop a further understanding on the robustness of the platforms and the development of inspection strategies:

- *Extend the dataset to include additional platforms*. The dataset used in this study consisted of a variety of platform types and configurations from around the world. As in the case of any dataset, additional information can improve the quality of results. Also, much of the data used in this project is related to simply framed older Gulf of Mexico platforms, which allows a first pass evaluation of platform performance using straightforward configuration issues (simple framing X or K, no skirt piles, etc.). However, there are a variety of other platform configurations used offshore, particularly in the North Sea. This recommended effort would involve gathering of new platform ultimate capacity information, perhaps from HSE files, and additional dataset evaluations. EQE or the HSE may also be able to obtain ultimate strength analyses from several operators, to input to the dataset perhaps for in-kind exchange of some portion of the results of the project.

- *Extend the results to more complex framing schemes*. This project focused on generally simple framing schemes – a necessary step in understanding platform robustness. However, other than shallow Gulf of Mexico platforms, more complex framing schemes are typically used offshore. This includes a combination of X, K, and single diagonal vertical bracing schemes all used in one structure, as well as, more exotic and complex 3D framing. In addition, there are other complexities that exist such as a variety of plan bracing schemes (X, diamond, diagonal, etc.), congested joints, balloon joints, and skirt pile framing. This recommended effort would involve a combination of additional 2-D (and perhaps 3D) ultimate strength analysis and additional data gathering and evaluation related to new platforms added to the dataset. While the two-dimensional frames study as a part of this project provided a good understanding of robustness, a study of the factors including, the effect of member sizing, out-of-plane bracing (3 D frames study) would provide further understanding of platform robustness. The focus would be to understand some of the more complex framing schemes that are typically found in North Sea platforms.

- *Develop a risk-based inspection planning process*. The work developed by this project provides an initial basis for prioritized inspections. However, as previously mentioned, there are numerous factors that must also be accounted for when developing inspection plans, for example, the consequence of failure of a platform (e.g., manned vs. unmanned), results of previous inspections and any known damage. These factors are mentioned in the current ISO and API inspection guidelines. EQE worked with BP Amoco to develop a risk-based underwater inspection prioritization process using various rules that were based upon experience and expert judgment. EQE has also developed underwater inspection philosophies in the recent Flooded Member Detection JIP. The information developed in the project described in this document, along with these other studies, provides a good opportunity to develop a risk-based inspection approach that can be used by the HSE to prioritize efforts associated with inspection planning and review.

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APPENDIX A

ELASTIC ANALYSES OF TWO-DIMENSIONAL FRAMES

- **X-BRACED FRAME**
- **K1 (K POINTED DOWN)-BRACED FRAME**
- **K2 (K POINTED UP)-BRACED FRAME**
- **SINGLE DIAGONAL (COMPRESSION)-BRACED FRAME**
- **SINGLE DIAGONAL (TENSION)-BRACED FRAME**

X-BRACED FRAME

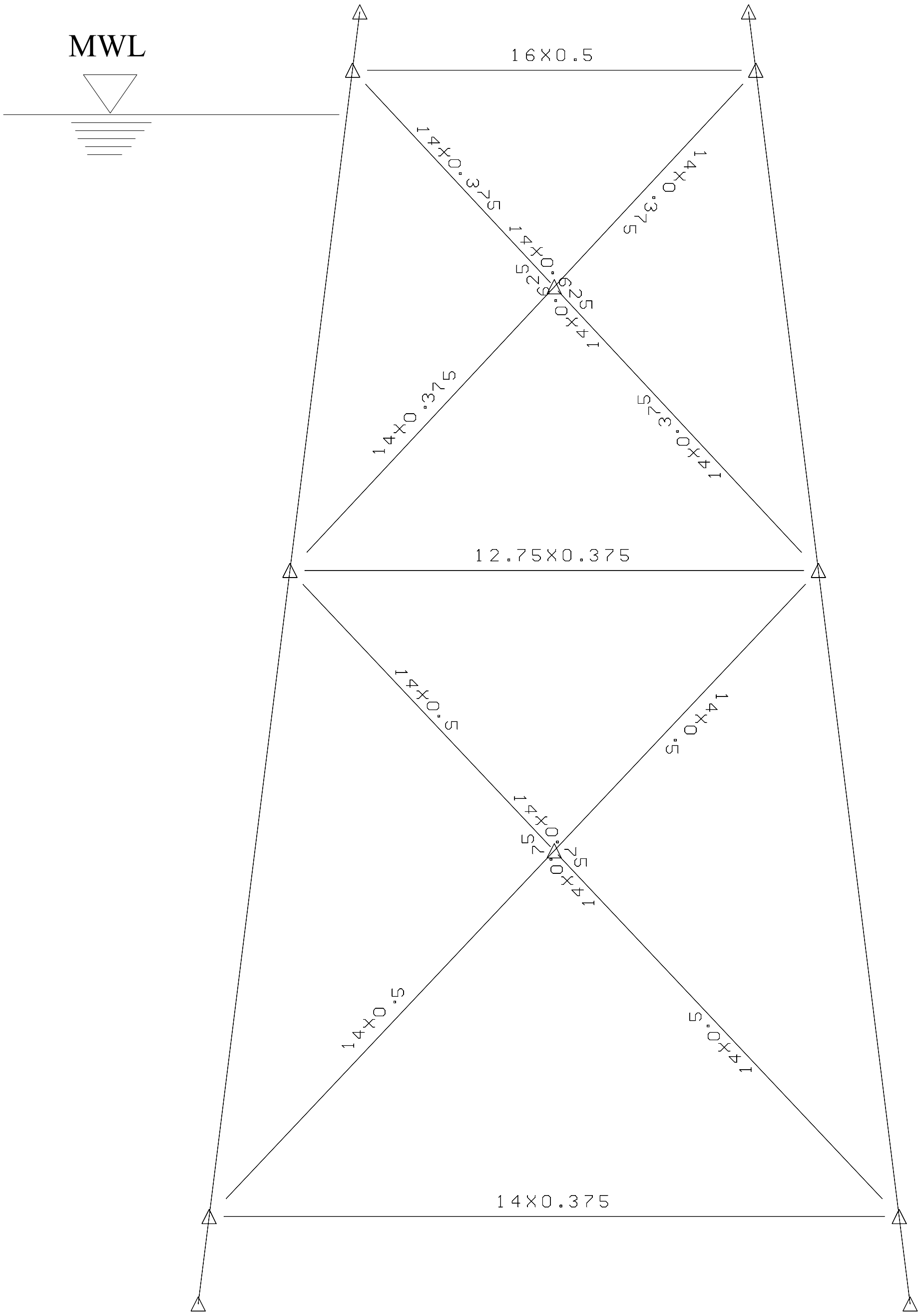

Figure A.1 X-braced Frame – Member Sizes

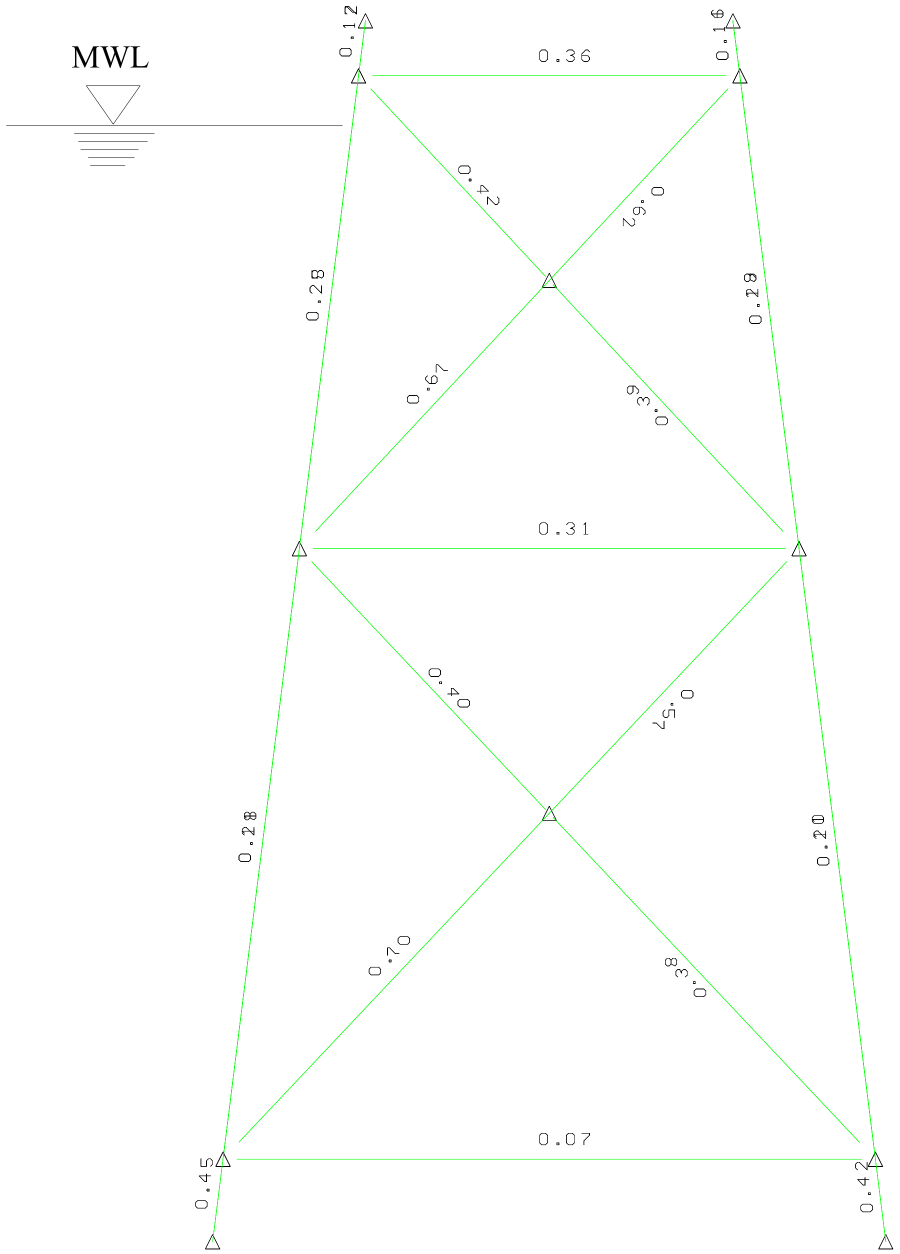

Figure A.2 X-braced Frame – Unity Checks

K1 (K POINTED DOWN)-BRACED FRAME

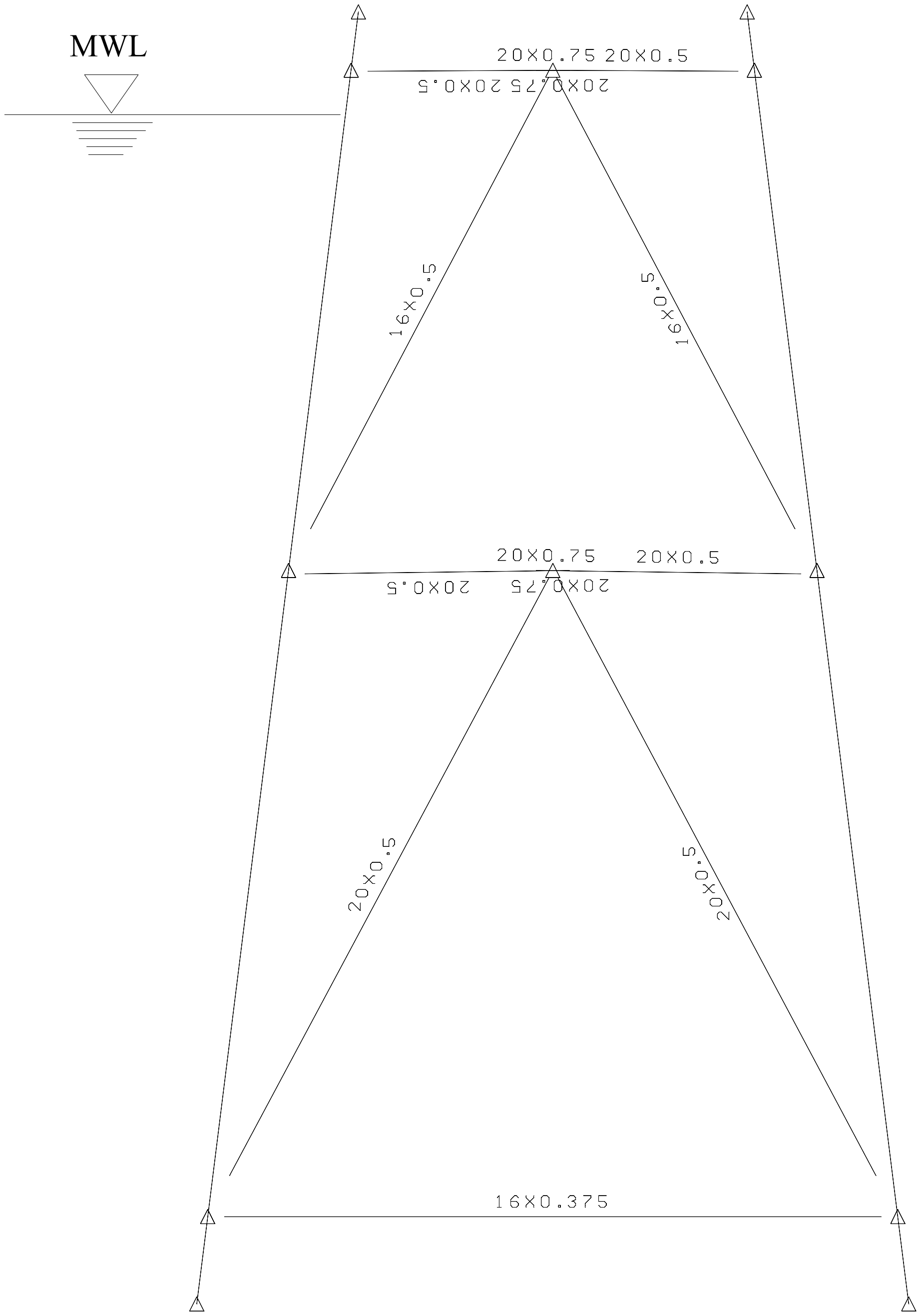

Figure A.3 K1-braced Frame – Member Sizes

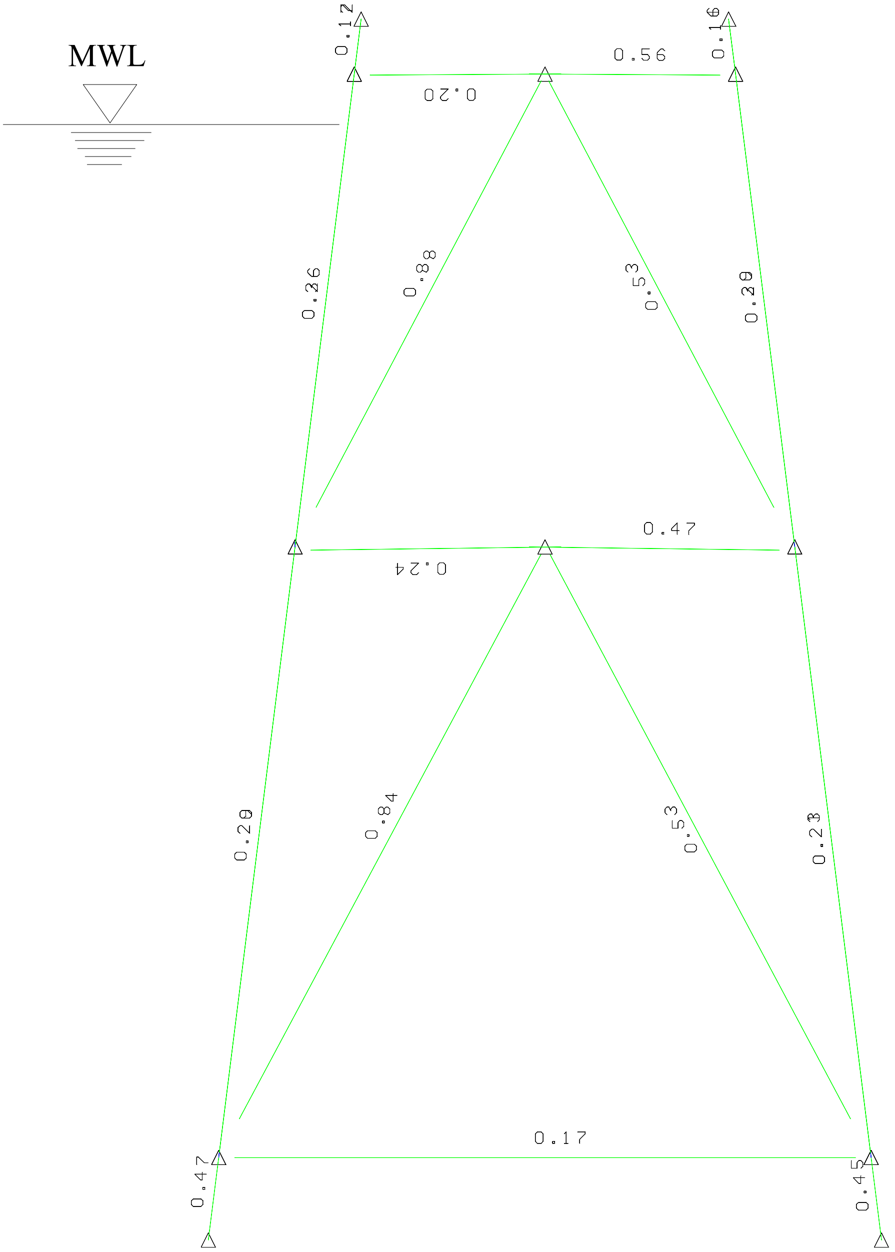

Figure A.4 K1-braced Frame – Unity Checks

K2 (K POINTED UP)-BRACED FRAME

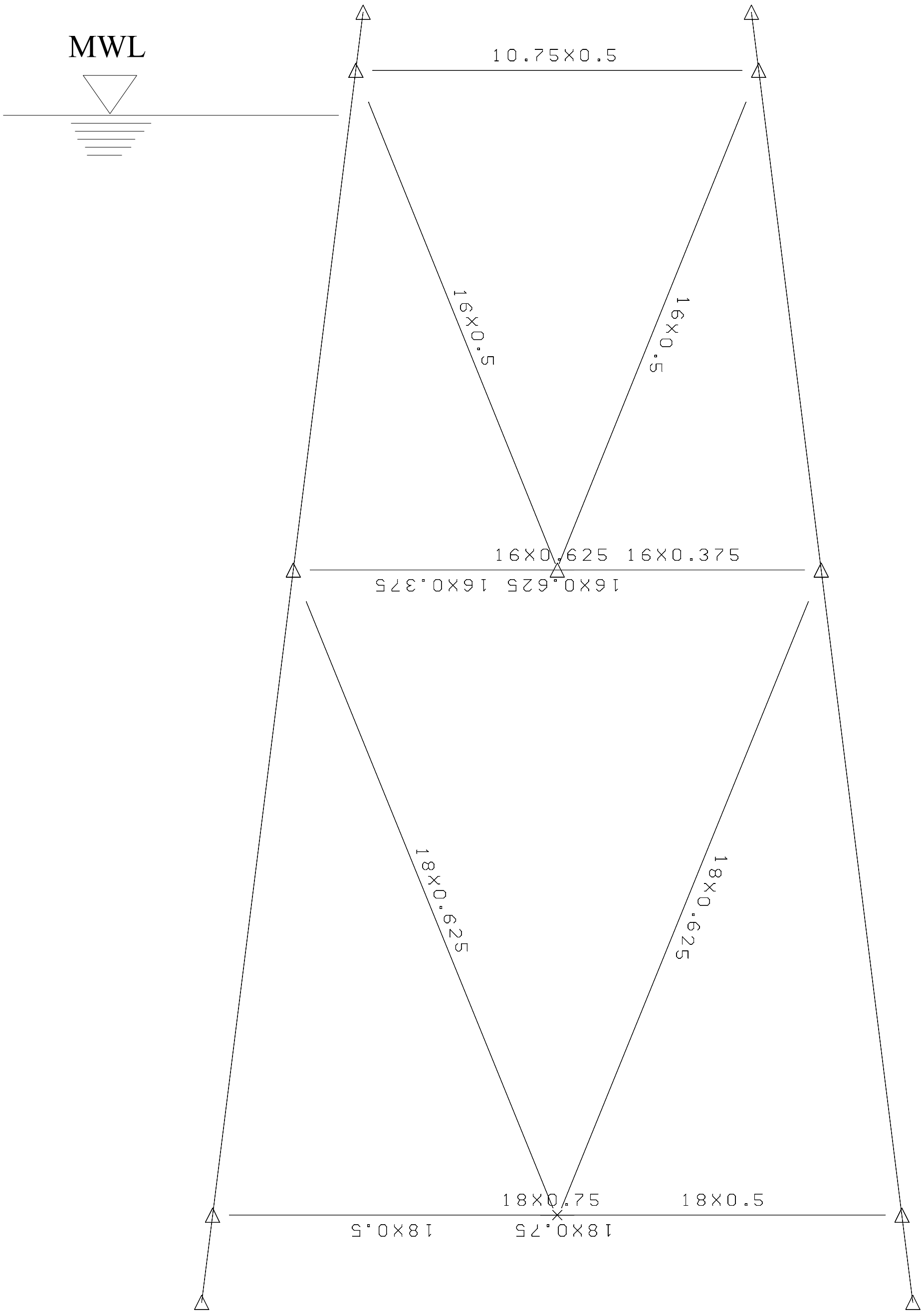

Figure A.5 K2-braced Frame – Member Sizes

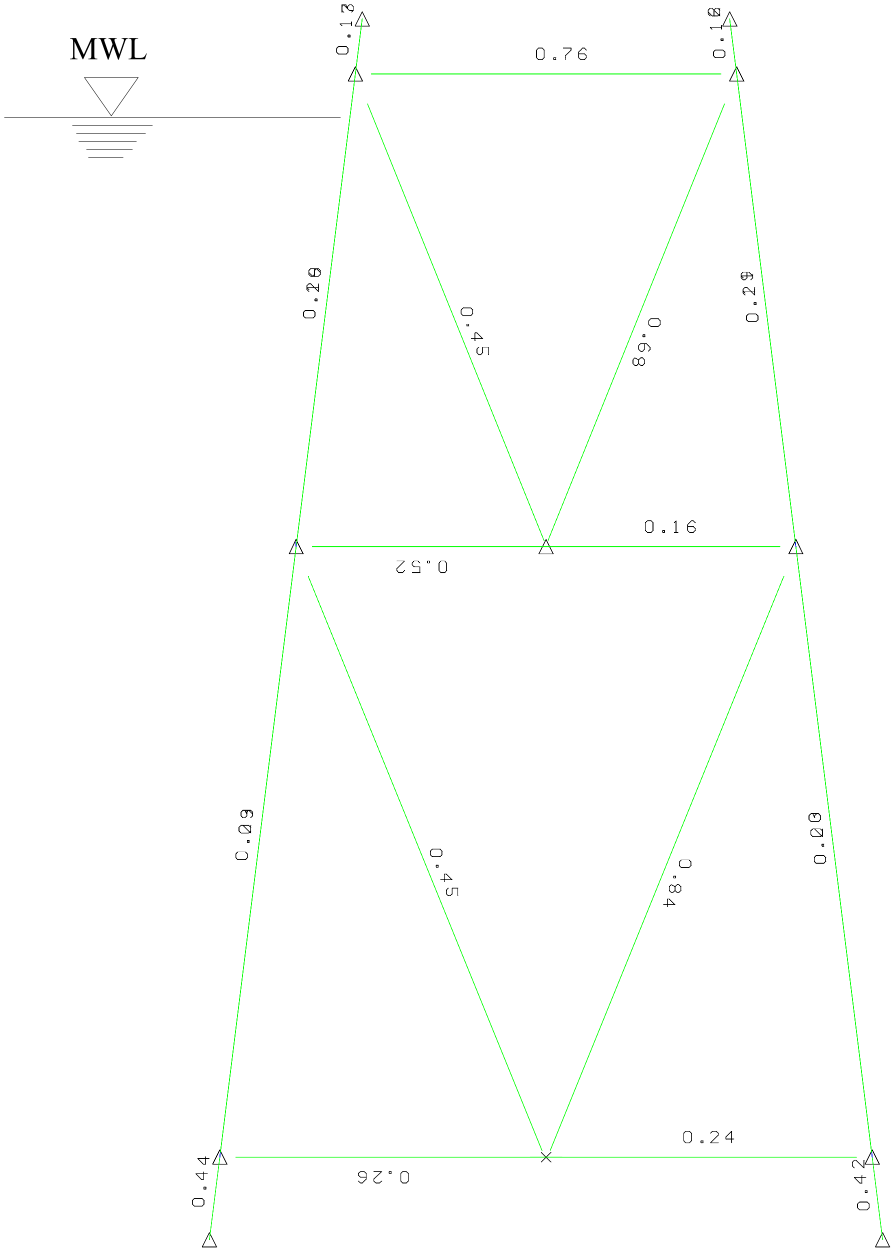

Figure A.6 K2-braced Frame – Unity Checks

SINGLE DIAGONAL (COMPRESSION)-BRACED FRAME

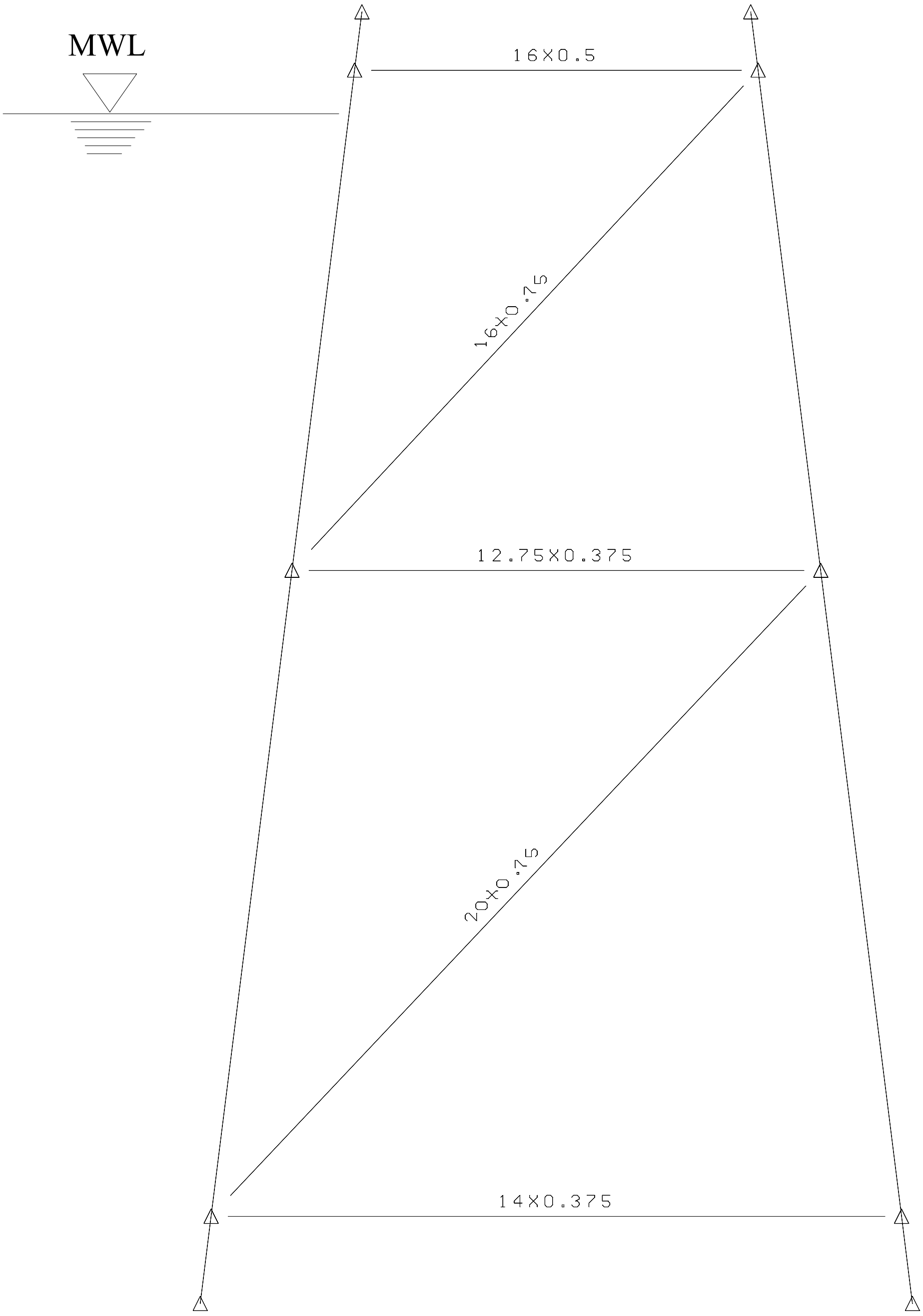

Figure A.7 Single Diagonal (Compression) – Member Sizes

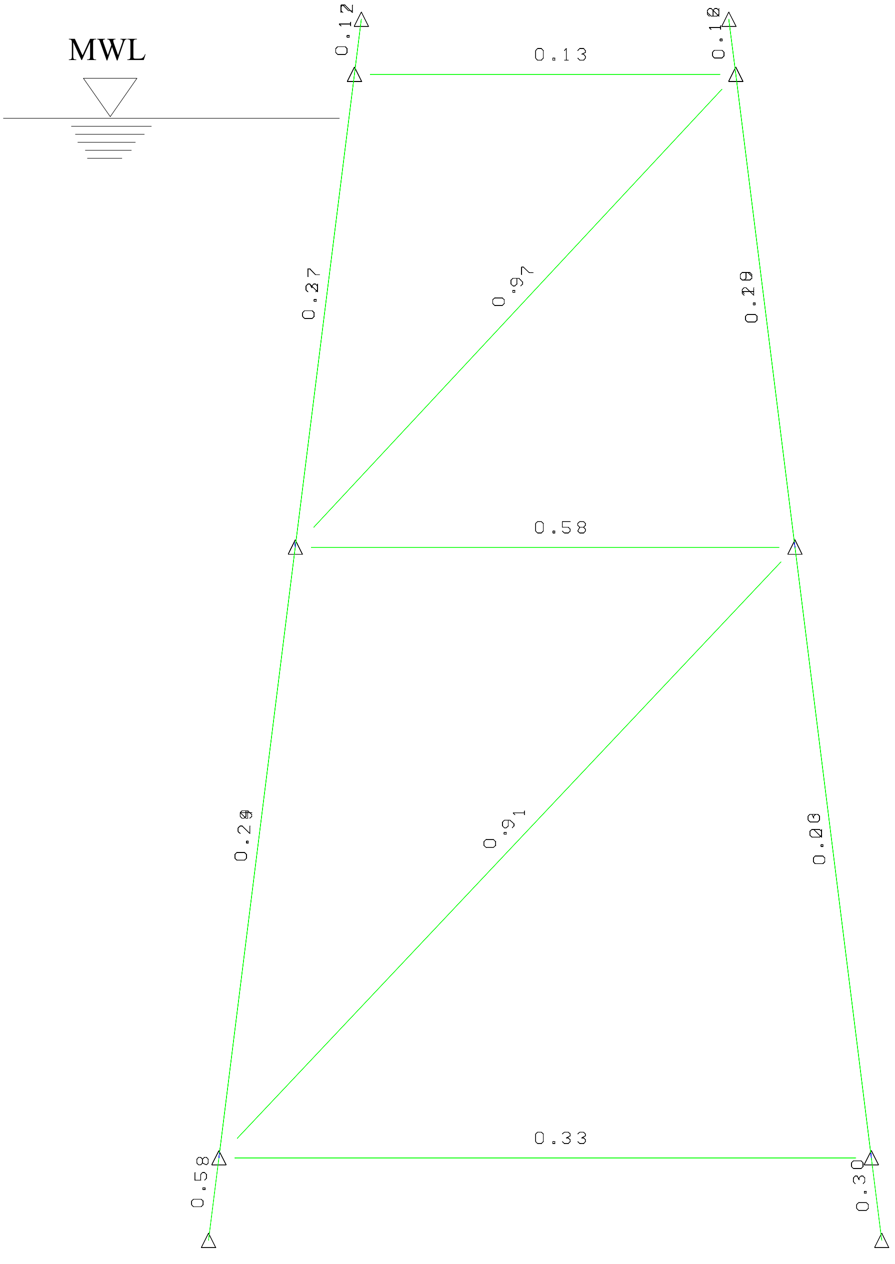

Figure A.8 Single Diagonal (Compression) – Unity Checks

SINGLE DIAGONAL (TENSION) BRACED FRAME

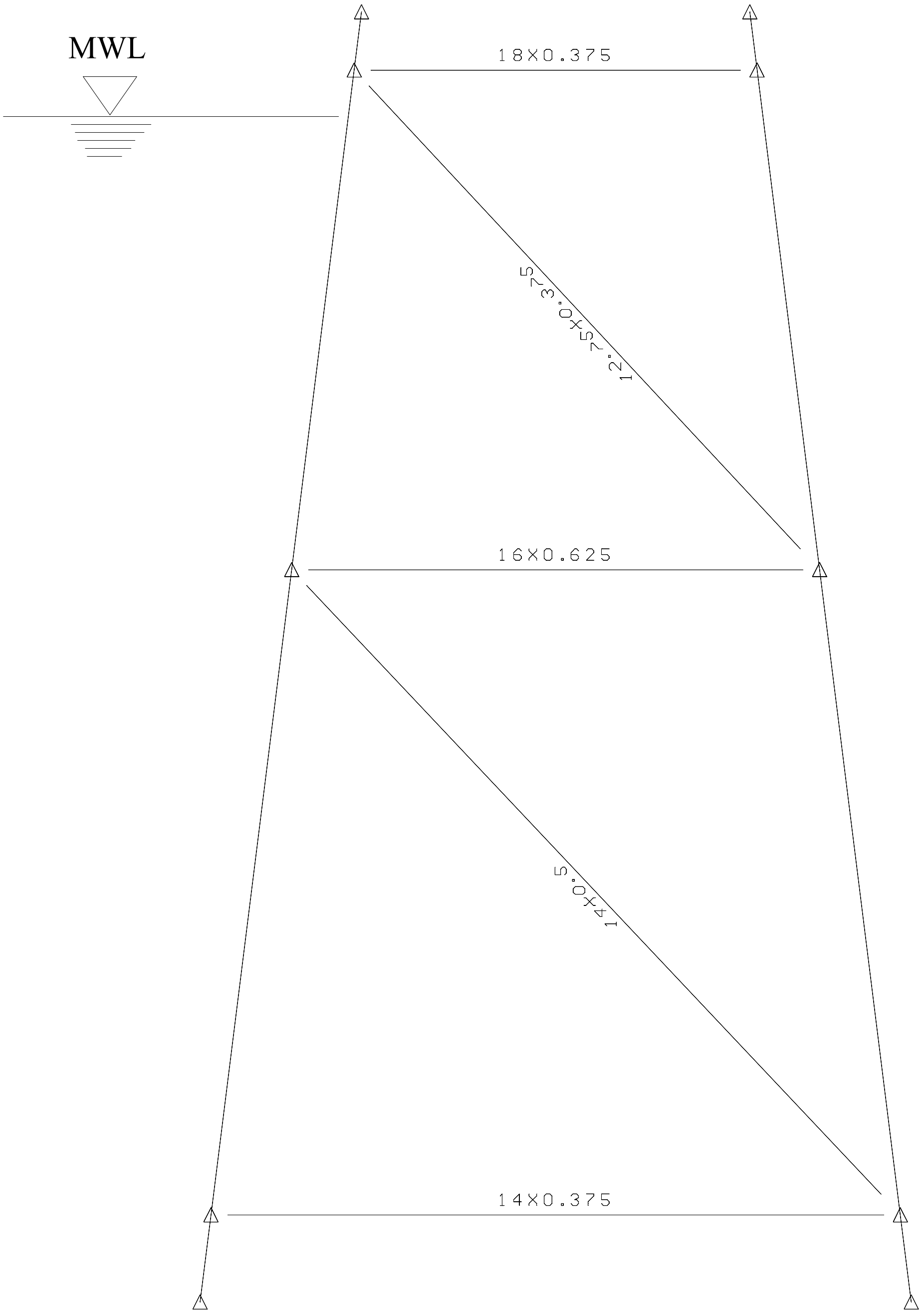

Figure A.9 Single Diagonal (Tension) – Member Sizes

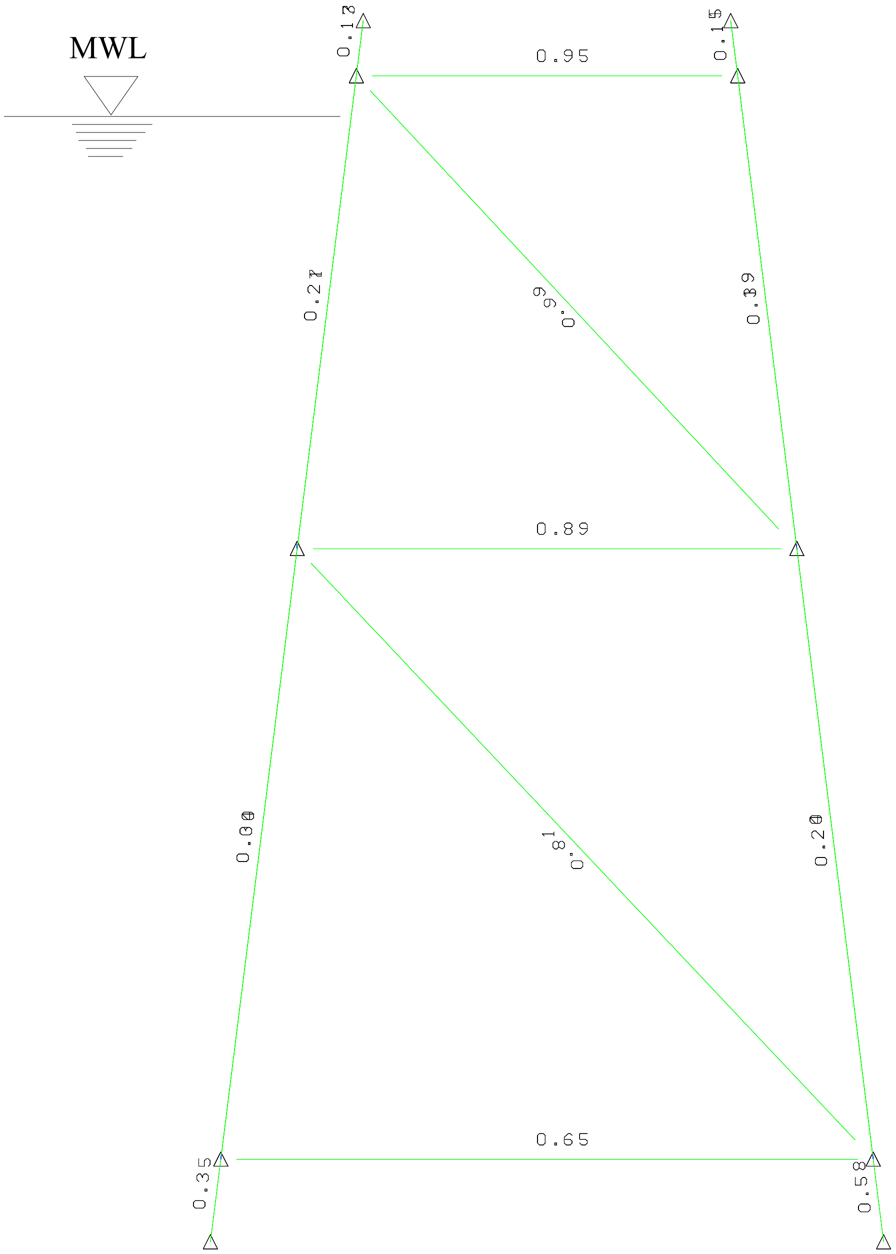

Figure A.10 Single Diagonal (Tension) – Unity Checks

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