COMPARITIVE STUDY OF EFFECT OF LOADING FOR OCEAN TRANSPORTATION & SEISMIC EVENT ON MODULAR STEEL STRUCTURES

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ABSTRACT: The Paper's intent is to study and compare behavioral difference of loading on steel structures under ocean transportation analysis and seismic analysis. This situation generally exists for a modularized steel structure (i.e. steel structure fabricated in shop and transported for erection). As Modularization of structures is becoming a trend in engineering there is a need to investigate further aspects of structural engineering for its efficient design. The objective of this paper is to determine the governing action of load for design of modular steel structures due to ocean transportation & seismic case for most of the seismic site classes.

Seismic analysis consist of loading due to ground motion acceleration where as ocean transportation analysis consist of loading due to barge acceleration on ocean waves and deck flexing action of barge. The Nature of load application in both the cases is similar however there is difference in structural behavior which is due to dissimilarity in Analysis parameters & amplitude of loading. This forms the basis for comparing behavior of structure during ocean transportation and seismic event.

Structure considered for study is a Process module of onshore oil and gas facility. Seismic loading considered is as per ASCE7-10. Seismic analysis is carried out based on Modal Response Spectrum method for site class D (Eastern Region of Asia - near Japan). Ocean transportation loading includes forces induced on structure due to deck flexing of barge (i.e. barge deflects due to wave action) and forces acting on the structure due to acceleration of barge on ocean waves. Specific data from marine engineering is used to evaluate ocean transportation loads.

Statistics is prepared comparing force coefficients, base shears, structural drifts, member unities etc. These results will present a relation of structural behavior during ocean transportation and seismic event for comparison purpose. To perform efficient design these results will allows engineer to highlight the most critical case of analysis governing the design.

KEYWORDS: Modularization, Module, Ocean transportation, Seismic, Barge, Barge acceleration, Deck flexing.

INTRODUCTION

Comparison of Ocean Transportation & Seismic Analysis

When analyzing structures we often consider various analysis cases to check whether the structure is safe and serviceable. (Analysis case here refers to different condition and forms of analysis such as site condition analysis, seismic analysis, wind analysis, ocean transportation analysis etc). Paper represent comparison of the analysis cases (i.e. Ocean transportation and seismic) so as to develop relationship with structural behavior/design. This comparison includes strength and serviceable condition of analysis such as flexure unity check, shear check, drift check, deflection check etc. Base shear is compared along with the distribution pattern of total lateral reactions at support locations. Similarly force coefficient and support reactions for both the analysis case are compared.

Ocean transportation analysis is only required when a structure is to be transported on Ocean/Sea (modularized structure). Modularization is a strategy to fabricate/construct a structure in fabrication yards/factories, transport and install it on site. Reason for making a structure modularized may be one or more of the following - cost, quality, schedule, site conditions, weather conditions, availability of resources on site etc. Seismic Analysis is required when a structure falls in a zone which is prone to earthquake & requires seismic forces to be considered for design as per countries/local regulations.

Seismic analysis consist of loading due to ground motion acceleration where as ocean transportation analysis consist of loading due to barge acceleration on waves and deck flexing action of barge. The basis for comparing behavior of structure during ocean transportation and seismic event is due to the fact that both the analysis case present similarity in structural behavior (loading due to acceleration) with variation in magnitudes which is due to variation in amplitude of loading and analysis parameters used for performing analysis, thus arises a need to compare both the analysis cases. Analysis parameters here refer to boundary conditions, code requirements, load combinations etc.

Structure Description

The Structure considered for study is a Steel Structure - Process module of onshore Oil & Gas facility. The structure is around 80m in length, 29m in width and 23m in height. Major weight components of structures are Mechanical equipments, Piping, Electrical equipments and cables, Architectural panels, Structural steel. These components make the total transported weight of module to be around 2700 MT. A case may appear where the total transported weight may be lesser then the operation weight of the module on site. These cases will require operation weight to be considered for seismic and transported weight for ocean transportation. In this paper the transportation weight and operational weight of module is considered to be same for obtaining more realistic case for comparison. The applicable live loads shall be considered for these cases respectively. RISA3D software is used to perform Analysis. A RISA model is developed for the structure. All applicable loads (including seismic and ocean transportation load) are applied on the structure to study its behavior.

SEISMIC ANALYSIS

Seismic Load is applied as per ASCE 7-10 with seismic parameters for site class D (Eastern region of Asia near Japan) as this form a high seismic zone. Response Spectrum Analysis (RSA) method is adopted to evaluate seismic response of structure as per section 12.9 of ASCE 7-10. Table 1 shows the site specific response spectrum data used to develop response spectrum curve. The parameters used for seismic analysis is shown in Table 2.

Table 1. Site Specific Response Spectrum

Period (Sec.)	0	0.03	0.05	0.1	0.15	0.2	0.25	0.3	0.4	0.50	0.55	0.75	1	1.5	2	3	4
Sa (g)	0.37	0.40	0.46	0.67	0.79	0.82	0.81	0.8	0.72	0.66	0.66	0.51	0.42	0.29	0.23	0.16	0.12

Table 2. Seismic Parameters

Item	Ss	S1	Fa	Fv	S_{DS}	S_{D1}	TL (Sec.)	Design Category	Site Class	I & Ip	Occupancy Category
Site Data	1.236	0.622	1.005	1.5	0.824	0.456	12	D	D	1	I I

Boundary condition for structural foundation considered is based on a site specific soil condition and foundation type. The site considered is eastern region of Asia near Japan and foundation type of steel piles is considered. Vertical stiffness due to soil parameters for a single pile is 315kN/mm and for horizontal stiffness it is 40kN/mm. Horizontal stiffness of 40kN/mm is the most common stiffness values used for piles so as to obtain reasonable seismic forces occurring at foundation. Soil-foundation stiffness evaluated for winter condition is considered as this form a critical case when comparing with other on-site cases. Number of piles at support location varies as per the structural loading requirement. Number of piles is not constant on each support locations thus the boundary stiffness will also vary accordingly and hence the base shear distribution will involve the effect of stiffness variation. However for ocean transportation analysis the boundary condition stiffness is same at every support location (described in OCEAN TRANSPORTATION ANALYSIS).

OCEAN TRANSPORTATION ANALYSIS

Ocean transportation loading are based on the most extreme condition of sea considering seasonal storm at least from a last decade. The worst part of the route is considered for performing the ocean transportation analysis. The route considered for analysis is in sea/ocean near Japan. Wind load on structure during ocean transportation has been omitted for simplicity.

For performing ocean transportation analysis it is important to consider two types of forces in barge. First is the differential settlement due to deck flexing (hogging and sagging) action of barge as waves of ocean will enforce the barge to bend upward or downward (refer Figure 1 - Part A), thus there will be a vertical displacement in the module imparting additional stresses in the structure. Second is the forces induced on the structure due to barge movement on ocean with the waves action. These forces induced are somewhat similar to the seismic forces induced on a structure (refer Figure 1 – Part B).

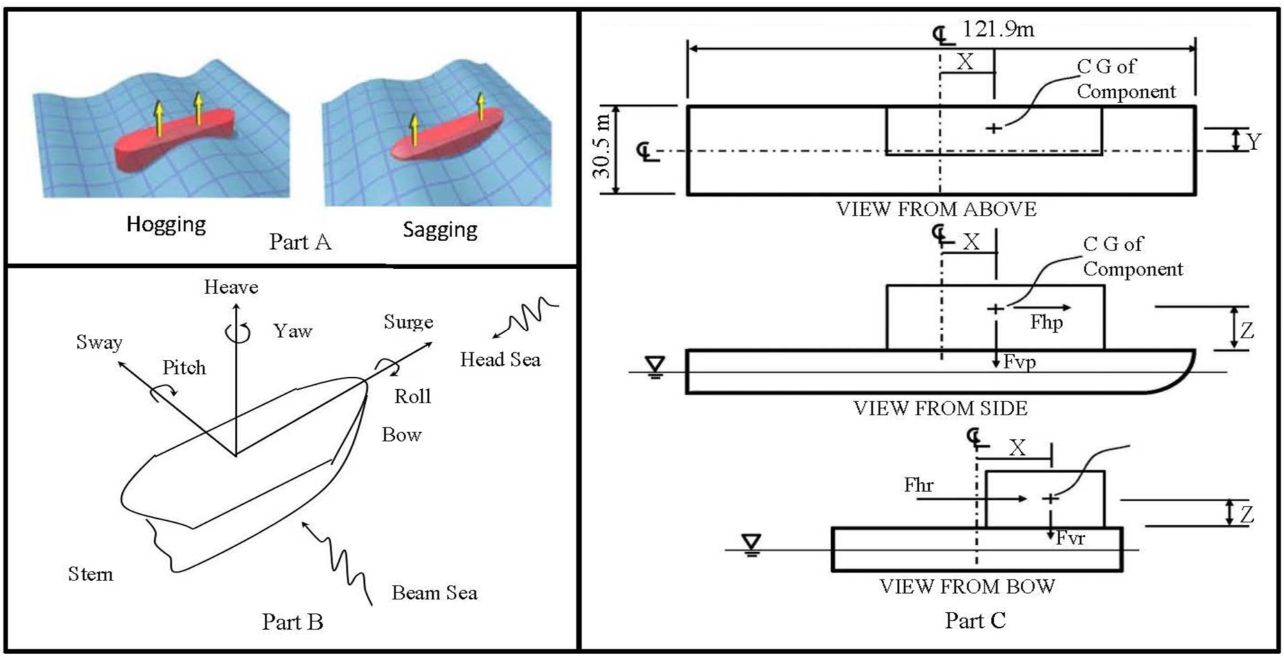

Figure 1. Part A shows Barge Hogging & Sagging action, Part B shows Barge motion and motion generated Forces, Part C shows Module placement on Barge and associated acceleration loading

Forces for acceleration of barge with wave action is applied similarly as ELFM of Seismic analysis with mass from structure applied in lateral direction at its respective level to account for lateral force components on the structure and vertical component of load is increased to account for additional forces due to barge acceleration. Coefficients are calculated based on a report from marine engineering with a specific barge parameters and is applied on the loads for performing ocean transportation analysis.

The force coefficient calculation is based on height variation and placement of module on barge as shown in Figure 1 – Part C (considering barge C.G. and centre of rotation of module is same). More the eccentricities between C.G. of Structure and C.G. of barge more will be the magnitude of forces developed on the structure. A barge of size 120x30m wide is considered for analysis. Module is placed along the centerline of barge on one of its end which forms a critical and reasonable case for ocean transportation analysis. It is important to note here that study was also conducted by placing the module on a corner in barge which exhibit more severe case as this will increase the vertical component from rolling action of barge. But for such large modules this case is highly uncertain and hence results for the same are not used for comparison purpose.

Following are the hog/sag values considered for analysis

a. Head sagging (Bs) = 95mm
b. Head hogging (Bh) = 45mm
c. Quarter sagging (Qs) = 45mm
d. Quarter hogging (Qh) = 30mm

Following are the value of Barge acceleration loading (as shown in Figure 1 Part C) considered in analysis.

a. Longitudinal Force Fhp = 0.21 * Weight

b. Transverse Force Fhr = 0.65 * Weight

c.i. Vertical Force (+ pitching component) Fvp1 = 1.57 * Weight } acts concurrently with pitching
c.ii. Vertical Force (- pitching component) Fvp2 = 0.46 * Weight

d.i. Vertical Force (+ rolling component) Fvr1 = 1.29 * Weight } acts concurrently with rolling
d.ii. Vertical Force (- rolling component) Fvr2 = 0.74 * Weight

Boundary condition of structure **-** The stiffness of barge deck is calculated based on deck stiffness and supporting arrangement which is considered here to be 525kN/mm in all three translational direction.

COMPARISON OF STRUCTURAL BEHAVIOUR

Both the analysis case i.e. seismic analysis and ocean transportation analysis is compared so as to judge the critical analysis case. The comparison is made for results of various structural parameters as shown below.

Force Coefficient Comparison

Horizontal Force Coefficient

It is significant from Table 3 that Transverse direction (Z) barge force coefficient is high which resembles the impact of rolling action of barge acceleration on the structure. However the Longitudinal direction (X) barge force coefficient is lesser as compared to Transverse direction which resembles the less effect of pitching action of barge acceleration on structure.

Vertical Force Coefficient

For Seismic case the vertical force coefficient Ev = 0.2 S_{DS} = 0.2 * 0.824 = 0.16 (Section 12.4.2.2 of ASCE 7-10). For Ocean case the vertical force coefficients are calculated from the barge acceleration values and are shown in Table 3. Vertical force coefficient includes the gravity weight. The Upper & Lower factors of Ocean transportation are critical as compared to respective seismic factors.

Table 3. Horizontal & Vertical Force Coefficient values for Ocean Transportation and Seismic Case

HORIZONTAL			VERTICAL					
Direction	Ocean	Seismic	Ocean				Seismic	
Transverse Direction	0.65	0.28	Pitching		Rolling			
Longitudinal Direction	0.21	0.28	Upper	Lower	Upper	Lower	Upper	Lower
-			1.57	0.46	1.29	0.74	1.16	0.84

Base Shear Comparison

Seismic base shear here is inelastic as it includes response reduction factor to calculate base shear where as for ocean forces it is elastic. This is done similar to resemble the actual approach adopted while performing both the analysis.

Table 4. Base shear comparison for Ocean Transportation and Seismic Case

Sr. No.	Description (Direction)	Ocean Forces (kN)	Seismic Forces (kN)	Comparison Factor*
1	Z- Base Shear (transverse)	17335	7508	2.3
2	X- Base Shear (longitudinal)	5646	7502	0.75

*Comparison factor = Ocean Force / Seismic Force

Longitudinal Direction

The graph showed in Figure 2 shows the magnitude of base shear variation along the length of the module. The Base Shear distribution pattern along the length of the module indicates similarity in action of loading for ocean transportation & seismic analysis. The Total base shear in longitudinal direction (X) from ocean transportation is only $3/4^{th}$ for that in seismic analysis. This shows that pitching action of barge does not have significant impact when compared with seismic force in longitudinal direction.

Transverse Direction

The support reactions also have similar distribution pattern of base shear for ocean transportation and seismic analysis in transverse direction. The total base shear for ocean transportation analysis in Transverse direction (Z) is more than 2 times the base shear from seismic analysis. This is due to the rolling action of barge which is dominant for ocean transportation analysis.

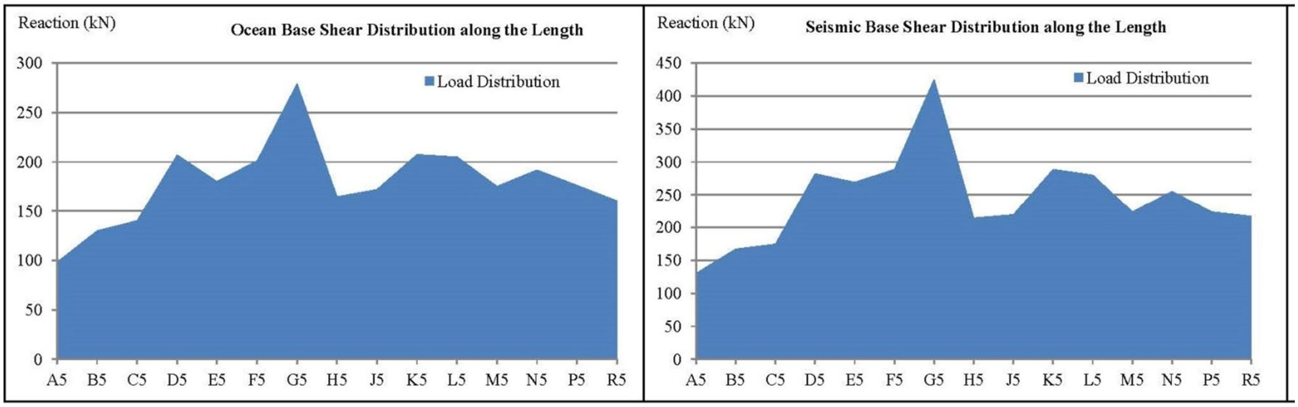

Figure 2. Base Shear distribution in longitudinal direction for Ocean Transportation and Seismic Analysis

Structural Drift

Structural drift for a grid with worst sway in transverse and longitudinal direction is compared as shown in Figure 3 & Table 5. The Structural drift for ocean transportation and seismic case are compared for respective serviceability load combinations. Table 5 shows Drift comparison for both the analysis cases.

Table 5. Drift comparison for Ocean and Seismic Case

Sr. No.	Description (Direction)	Ocean Drift (mm)	Seismic Drift (mm)	Comparison Factor*
1	Z- Direction (transverse)	82	27.5*Cd = 67.5	1.2
2	X- Direction (longitudinal)	43	16.7*Cd = 41.75	1.03

*Comparison factor = Ocean Drift / Seismic Drift

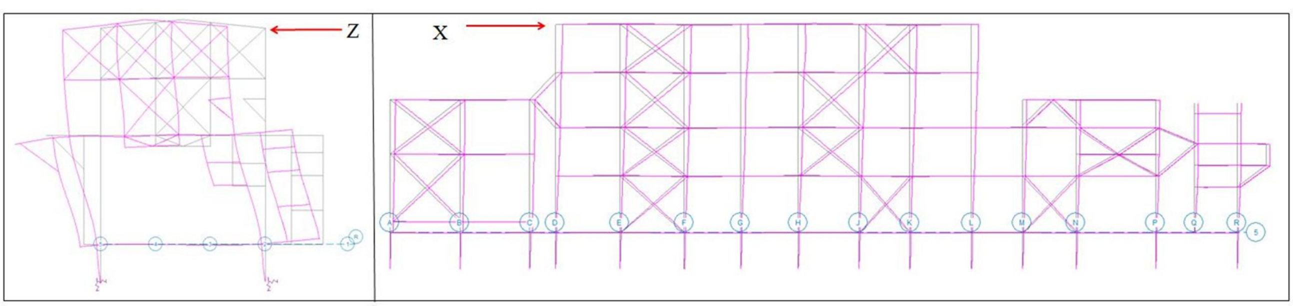

Figure 3. Side sway of Transverse frame (Z) & Longitudinal frame(X) for Ocean transportation and Seismic Analysis

Transverse direction

Behavior of structural drift in transverse direction is similar in both the cases. Comparing magnitude ocean transportation drift is nearly 1.2 times of that of seismic magnitude. The comparison factor is 2.3 for base shear which is dropped to 1.2 for structural drift this is mainly due to seismic design parameters C_d & applied load combinations.

Longitudinal direction

Behavior of structural drift in longitudinal direction is similar in both the cases. Comparing magnitude ocean transportation drift is nearly same as that of seismic drift. The comparison factor is 0.75 for base shear which is raised to 1.03 for structural drift this is mainly due to the effect of enforced deflection for barge sagging due to which the barge drift is raised considerably (transverse direction drift affecting factors such as Cd & load combinations are also applicable here). Hence it is important to note that the effect of barge sagging and hogging due to wave action which is an additional effect in ocean transportation case plays a significance role in deciding the structural configuration.

Strength Check of Member in Flexure and Shear Unity

For member design in flexure unity and shear unity it is more relevant that ocean transportation analysis case governs. Most of the members in a system govern for ocean transportation analysis, as also shown in the Figure 4 and 5. A brief comparison as an example is shown in Table 6 indicating unity for girders in different range group, resembling ocean transportation analysis is critical than seismic analysis.

Following is the comparison of strength check of members in Flexure unity & Shear unity for base frame and for Main Force Resisting system in Module. Highlighted portion shows the most critical region and color coding used to highlight the unity variation.

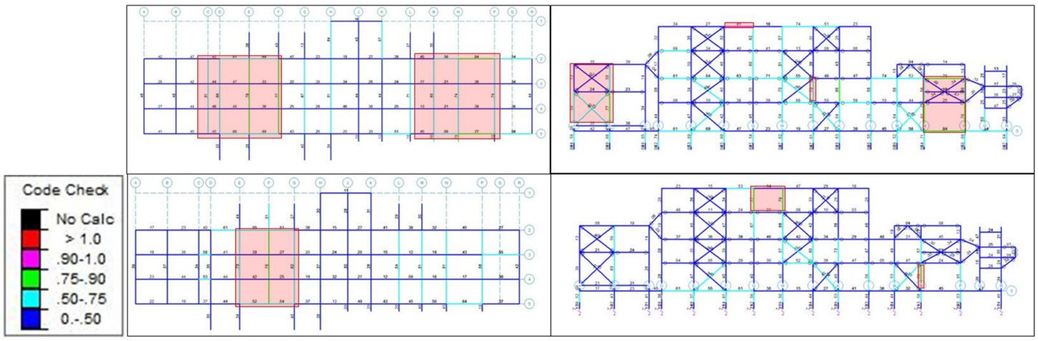

Figure 4. Unity Check of Girders (left) & Longitudinal Frames (right) for Ocean transportation (Top Snaps) & Seismic (Bottom Snaps)

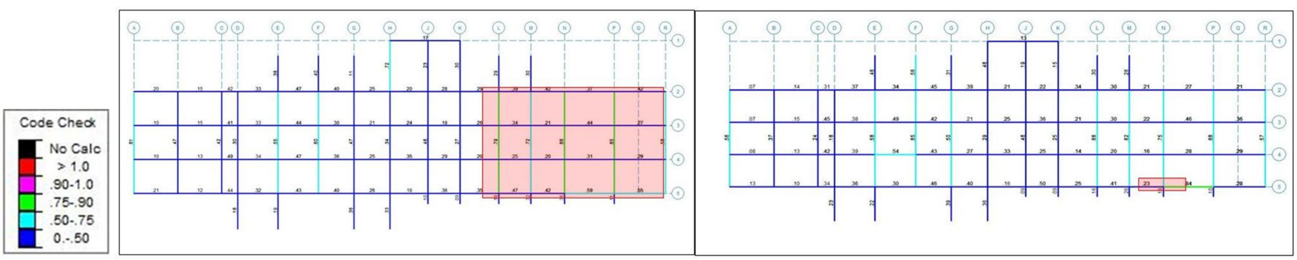

Figure 5. Shear Check of Girders for Ocean transportation (Left Snap) and Seismic Analysis (Right Snap)

Table 6. Unity Ratio (Flexure and Shear) comparison for Ocean Transportation and Seismic

Unity	Seismic		Barge		Remarks
	Flexure	Shear	Flexure	Shear	
Maximum	0.751	0.844	0.845	0.863	Most critical girder unity
< 0.5	73	78	65	79	Value shows No of girders
0.5 - 0.7	15	10	17	6	
> 0.7	2	2	8	5	

Deflection Check

It is relevant from all comparison factors (refer Table 7) that deflection check again will be more critical for ocean transportation case. The results highlighted in Table 7 is an example which also show ocean transportation will have more critical members to be checked for deflection with lesser values of length/deflection. Table 7 also shows the range of length/deflection and number of girders lying in this range just to highlight the structural behavior; these numbers will not have much significance once it is out of range of allowable limit for deflection.

Table 7. Deflection comparison for Ocean Transportation and Seismic Case

Length/Deflection	Ocean	Seismic	Remarks
Minimum	352	543	Value
<500	4	0	Number of Girders lying in the range specified
500-1000	0	11	
1001-2000	23	12	
2001-3000	8	10	

Support Reactions

Below is a comparison showing strength level support reactions for both the cases (refer Table 8) arrived at by considering the applicable load combinations used for design. The support reactions are shown for a worst case of load combinations at a single support location. The seismic support reactions will be used to check the pile strength and foundation design while the barge support reactions will be used to design the connections between module and barge. The significance of support reaction for both the cases are different and there are number of factors influencing the variations however results are presented so as to get a sense of relationship for situations where support reactions will be used.

Table 8. Comparison of Support Reactions for Ocean Transportation and Seismic Case

Force	Ocean	Seismic	Comparison Factor*
Shear (X) - Longitudinal	370	530	0.7
Shear (Z) - Transverse	1460	1120	1.3
Compression (+Y)	4120	4610	0.9
Tension (-Y)	1990	760	2.6

*Comparison factor = Ocean Force / Seismic Force

CONCLUSION

From the comparison of various structural parameters in previous sections it is observed that ocean transportation analysis plays a vital role in deciding the structural configuration and member design as this case usually governs. Another significant observations from the results shows that serviceability requirements for seismic case should be given equal importance as its code conditions may be more stringent. It may be convenient for an engineer to decide the structural configuration and member sizes initially from ocean transportation analysis. However it is essential to perform a check for seismic analysis so as to confirm the overall safety of structure mostly where serviceability requirements governs the design. This paper shows a case where ocean transportation parameters and seismic parameters are for a critical case of loadings and are nearly same. An engineer can use this scenario as a benchmark for comparing and deciding the governing case for a modular structure design. For a case where these parameters resemble reflective changes engineer may be required to perform a separate analysis. However these results can be considered as a driving factor for judging the criticality when comparing the two cases.

DISCUSSION

The more irregular case of analysis will be ocean transportation when comparing both the cases as seismic analysis will always remain constant for an applicable site class whereas Ocean transportation analysis depends on several factors such as type of barge, placement of module on barge, connection between module and barge, route of transportation and associated action of sea etc. For getting less severe ocean transportation forces the solution would be to place the module on the barge at a location where the combination of barge acceleration forces and barge deck flexing is minimal. This may require a good co-ordination with the barge contractor to place the module on barge at a location which is useful for design. For Seismic event the design practices and considerations are known to all while ocean transportation event is a unique case which is conventionally not encountered. Importance should also be given to detailing requirements of structure for ductile design in seismic case or for fatigue due to transportation for ocean transportation case. Ocean Transportation analysis also includes ensuring the structural strength and stability of barge/ship, addition connections design for interface between barge and modular structure etc. Connection arrangements (refer Figure 6) required for ocean transportation of module typically includes Barge transportation beam which is required to distribute the total module weight on the transverse frames of barge structure. Outrigger beam and tie downs are connection between module and barge transportation beam. Uplift clips are required to restrict the uplift of barge transportation beam and hence the module. Similarly Longitudinal & Transverse clips are required to restrict longitudinal & transverse displacement respectively.

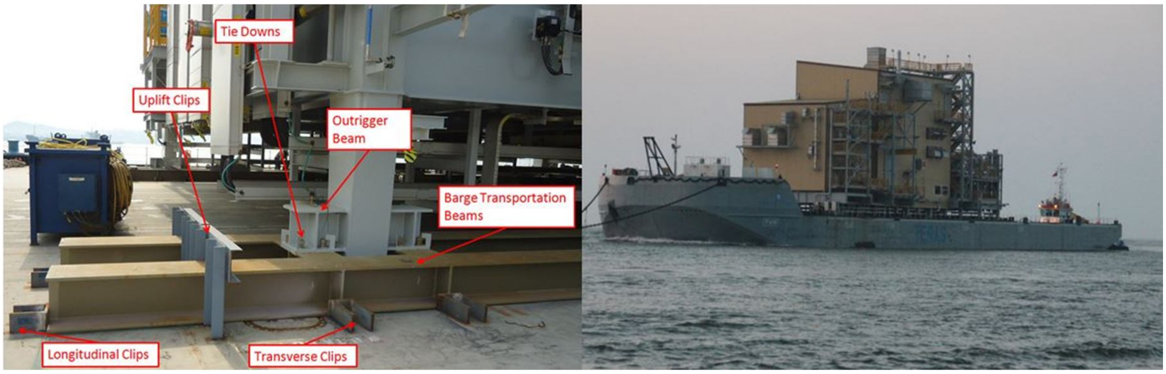

Figure 6. Structural arrangement required for a typical Ocean Transportation of Module (left) and an Image of Module on Barge (right)

REFERENCES

[1] ACSE 7-10 Minimum Design Loads for Buildings and Other Structures