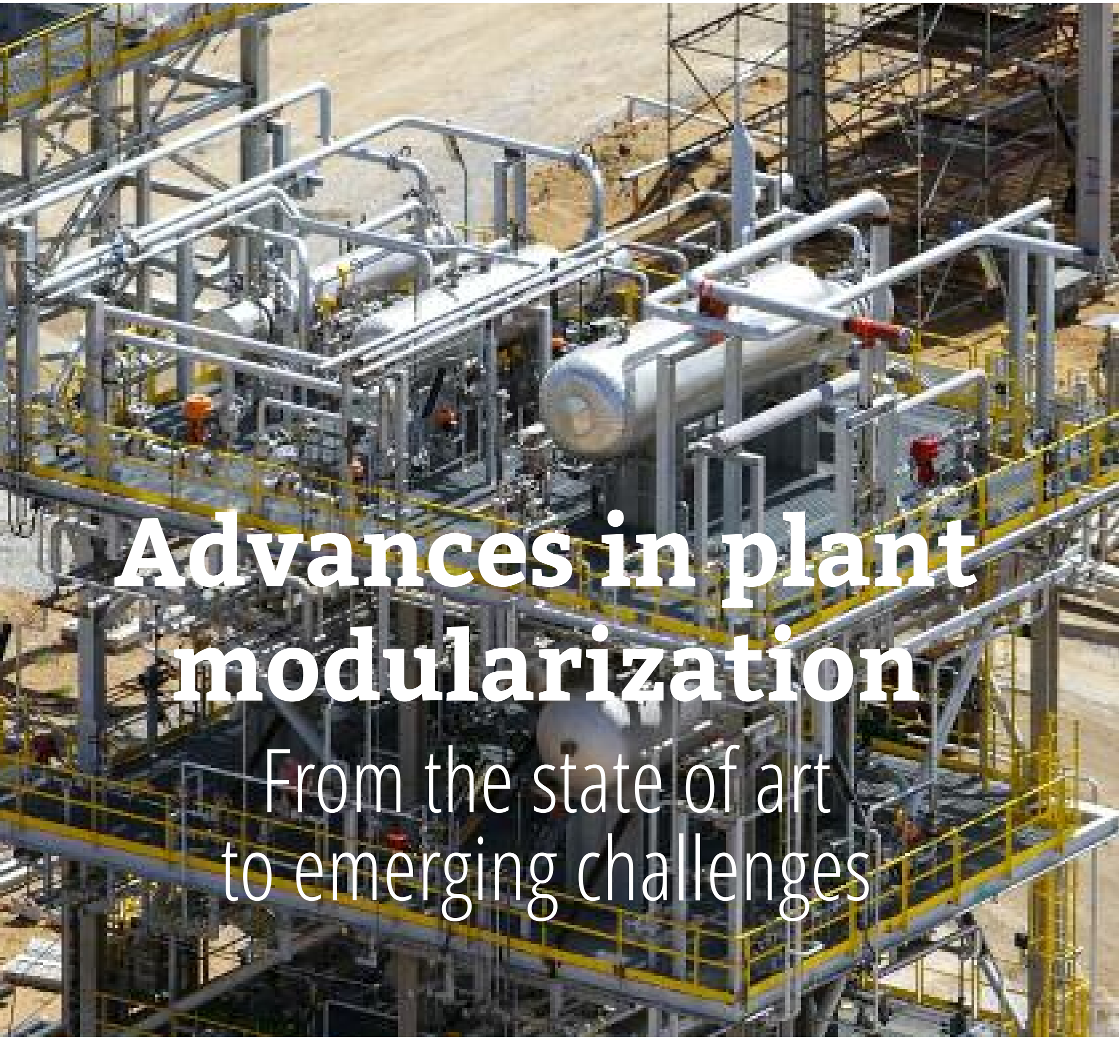

Advances in plant modularization

From the state of art to emerging challenges

Edited by **Mauro Mancini**

with the support of eci European Construction Institute

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Preface

I'm proud to introduce this publication that could be the first volume of a series aimed at boosting innovation and at capitalizing lessons learned in the Engineering and Construction Sector. Industrial plant modularization represents one of the main drivers for the innovation and competitiveness of both clients and main contractors in the future decades. Modularization is the basis of power plant flexibility (both in the management of large power plant fleets and in the ordinary single plant exercise) that will become the real turning point for the new generations of industrial plant engineering and management approaches.

ANIMP's main mission is to support the sharing of Industrial Plant culture all over the world through its technical chapters that merge the experiences of the Associated Companies in the specialist disciplines. The over cited collaboration between Industrial Companies and Universities in the industrial plant engineering and management is efficiently and practically expressed by this initiative of the ANIMP Construction Section that proposes a reference for spreading and divulging industrial plant culture and best practices. I hope that this way of working will drive the future challenges of the Association.

Nello Uccelletti

(President of ANIMP)

Credits and acknowledgements

The book is based on data, opinions, procedures and designs shared by the members of the ANIMP-ECI Task force on Modularization. The experience and knowledge emerged during the vivid and fruitful discussions within the Task Force in the last two years are the real origin and the strength of the research.

Under these premises, Chapter 1 and Appendix A has been written by Mauro Mancini and Nicola Careri; Francesco Di Serio and Alistar Gibb significantly contributed to the paragraph on “Discussion and improvement areas”. A special thanks goes to Paolo Androni who supported the overall activity within his MS thesis work at DIG – Politecnico di Milano - and to Tristano Sainati (FARB researcher) for the design of the questionnaire.

Chapter 2 has been written by Paolo Cremonini, Gabriele Scandolo and Loris Giovannini from Fagioli S.p.A.

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All the industrial members of the ANIMP-ECI Task Force reviewed the entire text under the coordination of Marco Spinelli.

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Mauro Mancini

(Delegate of ANIMP Construction Section)

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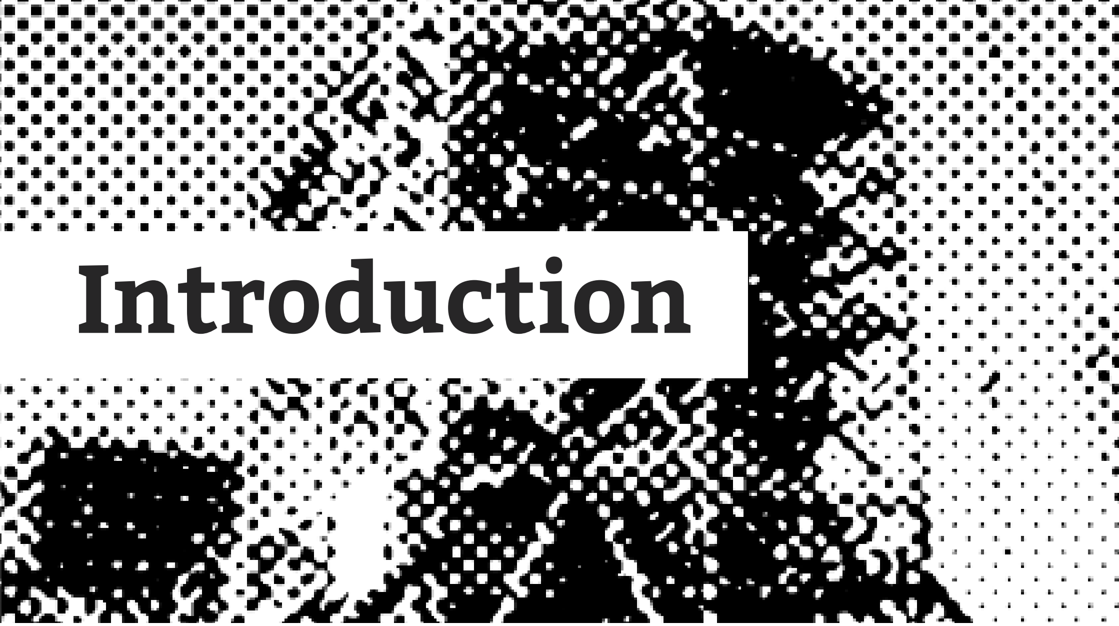


Introduction

"Is modularisation a suitable execution strategy for our industrial plant project?"

This is the question that is being asked more and more among plant EPC contractors and clients.

Modularisation is a forced choice in the case of off-shore installations and a cutting-edge design paradigm within the nuclear plant sector [1] [2] [3]. This construction approach in the last few years has been applied also by petrochemical, chemical, gas processing and oil refining onshore plants. In 2008, North West Shelf Venture Phase V in Western Australia was the first LNG plant to realize this conception, but since then several Liquefied Natural Gas (LNG) plants have been using this execution strategy as well [4]. Other recent examples of plant modularisation are the expansion of an existing refinery that Saipem is performing in Suriname(1), the new units realized by Foster Wheeler in a refinery in Belgium as well as three plants designed by Technip in North Alberta (Canada) for the Horizon Oil Sand Project between 2005 and 2012(2).

What is a module?

A plant module is a transportable, prefabricated/preassembled steel structure containing static and rotating equipment, piping, instrument, electrical hardware and associated cabling that can be constructed and pre-commissioned in areas with controlled conditions that differ from the final location. These areas are called yards. After the assembly in the yard, the modules are transported (by road or sea) at site for final installation and integration in the final plant.

These type of projects stimulated ongoing analysis and a still developing literature, focusing on a modular approach to construction, its basic dimensions and the main drivers that lead to the choice of this particular execution strategy.

Nevertheless, due to the strict confidentiality that covers such projects, three elements are still missing from a full understanding of modularisation potential:

- a systematic comparison between concepts expressed in literature and actual practices;
- an assessment of these practices aimed at identifying gaps to fill in order to make modularisation a fully operational and ready to use approach;
- an analysis of the identified technical criticalities focused on providing general and on hand design solutions

In order to fulfil the threefold purpose of this work a survey was first conducted among the main Italian Engineering, Procurement and Construction (EPC) contractors and some service providers. This survey allowed the comparison of drivers, barriers and dimensions generally associated with

Figure 1.1 - One of the pre-assembled units for the Woodside-operated Train V Phase 5 LNG expansion facility at Karratha, Western Australia.
Image: Courtesy of Woodside Source: Foster Wheeler

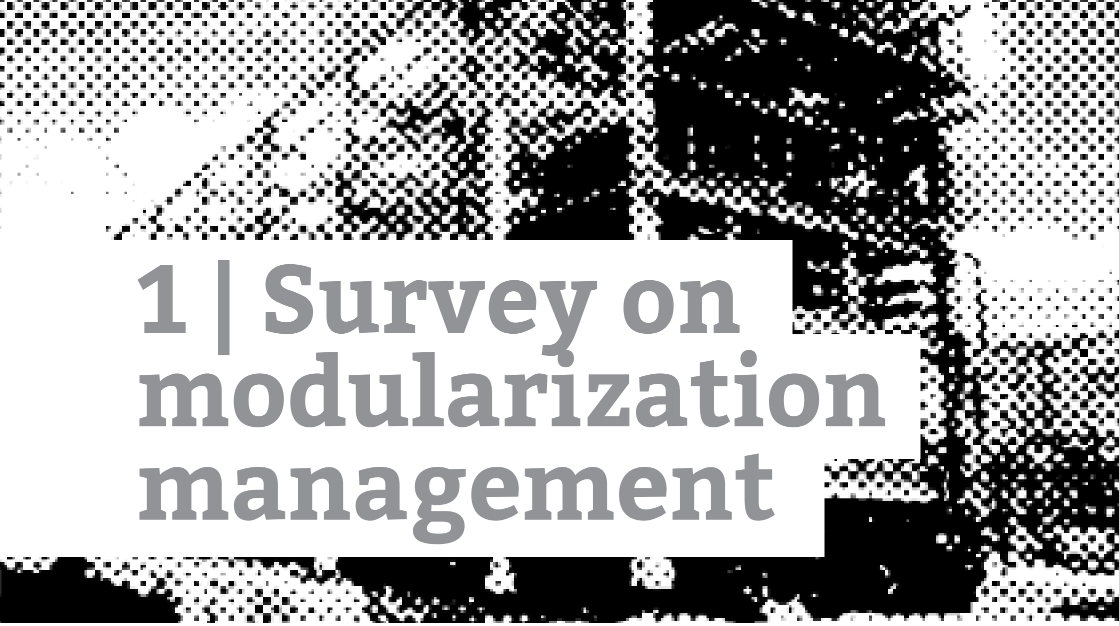
(1) http://www.saipem.com/site/home/press/by-year/articolo6121.html

(2) http://www.technip.com/en/press/technip-awarded-two-major-contracts-horizon-oil-sands-project-canada

modularisation with the actual perceptions of a significant sample of the Italian EPC supply chain. Next, starting by considering some technical criticalities highlighted by the survey, a case study was developed dealing with some crucial issues in module design, in order to provide valuable and innovative engineering solutions.

The exposition of the work is organized as follows: chapter one regards the survey and consists of four sections: the first one presents the literature review, with particular reference to drivers and criticalities generally associated with modularisation; section two explains the questionnaire structure highlighting methodological aspects, enlisting the companies involved in the survey and specifying the interviewed roles; the third section presents and analyses the interview results; section four discuss the results identifying improvement areas and some design gaps to be filled in order to enhance modularisation operability and application range. The second chapter is devoted to the criteria for module handling, including sea transportation and land transportation via SPMTs. The third chapter describes instead the proposed technical solutions from the structural point of view, on the basis of the analysis of a case-study. More specifically, the third chapter treats some specific issues which are of crucial importance in the achievement of the following objectives, strictly related to modular plants: preservation of the structural safety; optimization of the structural weight; increase of the structural versatility. The suggested modifications to the structural layout of the case-study can be considered of general validity for modular plants. Finally chapter four summarises results and recommends key future areas to develop.

Figure 1.2 - **Modularized steam reformer furnace for hydrogen production unit, designed and built by Foster Wheeler for a plant in Nigeria.
The 750-ton weight heater was delivered completely assembled.**
Source: Foster Wheeler



1 | Survey on modularization management

1.1 Literature overview

Recent literature on modular construction agrees that modularisation is everything except that silver bullet [5]. Caswell et al. [6] reinforces this point eloquently, stating that: modular construction is an appropriate execution strategy, particularly where the following circumstances apply [5] [7]:

- Very high labour cost at site
- Very low labour productivity at site
- Wide lack of skilled manpower in the region/area of the site
- Lack of adequate infrastructure to host a high number of expat workers
- Restrictions on maximum number of allowed expat workers
- Constraints on maximum number of workers simultaneously operating at site
- High probability of severe weather conditions during the construction phase at site
- Serious safety/security concerns at site
- Need for a project crashing
- Significant need of resources subject to high competition among the company's project portfolio

- Environmental, legal or regulatory constraints at site

Under these circumstances, which come together particularly in remote areas as well as in areas where there is a high demand of labour, a modular approach may offer significant advantages compared to a traditional stick-built construction strategy. These advantages are derived mainly from shifting a considerable amount of work from the site to one or more fabrication yards located in strategic areas [4] in which sufficient skilled and cost-effective construction manpower is available [5]. Yard fabrication allows modules to be produced in an efficient, safe and controlled environment using a lower cost skilled workforce and achieving high quality standards. Furthermore performing the construction in different locations simultaneously and bringing the modules to the site afterwards, may yield savings in project execution time. The above advantages have been summarized in Table 1.1

Modularisation benefits	
Schedule Savings	Higher Safety
Improved quality	Higher Security
Social/Environmental Impacts reduction	Lower Manpower costs
Reduction of weather impacts	

Table 1.1 - **Modularisation benefits generally recognized by literature**

Besides these boundaries dependent advantages, modularisation also has some disadvantages that may affect the whole project lifecycle. A list of the disadvantages most frequently associated to modularisation in literature, is provided in Table 1.2

Modularisation drawbacks	
Higher engineering effort	Higher structural costs
Higher transportation costs	Higher need for infrastructure
Local content impacts	...

Table 1.2 - **Modularisation drawbacks generally recognized by literature**

What arises from this literature overview is a clear perception of modularisation as a strategy to reduce overall project risk, under some bound and determined hypothesis. What is not clear is how much this common perception is shared by the EPC contractor supply chain, and how much weight companies and operators give to the above aspects. Furthermore is not clear which gaps need to be filled in order to completely deploy modularisation's potential. Research was conducted to shed light on these matters by means of a survey among some main actors of the Italian EPC contractors supply chain.

Definitions	
Module	A module consists of a volume fitted with structural elements, finishes and process components to be easily integrated in a plant due to "well defined" interfaces. Modules contain prefabricated components or preassemblies and are constructed away from the construction site. Module weight typically varies between 50 and 6000 tonnes. Module size is essentially determined by fabrication facilities, transportation & logistic constrains, offloading facilities, module handling, heavy lift and hook-up, technical solutions, maintenance and operability, site limitations and client requirements.
	Modules with dimension in the order of 6x6x30 meter up to 100 ton that can be transported by truck are usually called "small modules"
	Modules with dimension in the order of 72x42x36 meters and weight up to 6000 tons are usually called "large modules". Large modules require sea transportation.
PAR (Pre-Assembled Rack)	A typical steel pipe-rack module (PAR) installed on concrete plinths or sleepers enabling piping/cable interconnection and distribution between all the plant areas
PAU (Pre-Assembled Unit)	A structural steel box designed to include one or more pieces of process equipment, piping, electrical and instrument item.
Skid/Package	A popular method of distributing and storing machinery. Simply put, the machinery at point of manufacture is permenently mounted in a frame or onto rails or a metal pallet. The equipment can then be easily and securely transported and used as a unit. For example, a fire fighting skid unit may also be temporarily placed onto a vehicle to equip it for its task

Table 1.3 - **Table of common terms**

1.2 Survey features

As shown in Table 1.4, the questionnaire was completed by six Italian EPC main contractors and one service provider. Nineteen different managers from five different departments were interviewed to get insights from each EPC's business area.

The information was collected through guided interviews. In each interview a broad introductory discussion was followed by the survey compilation. The twofold objective of the introductory discussion was to explain the main objectives and motivations of the research and to let the interviewees describe their concrete experience with modular projects. This produced new insights on modularisation derived from on-the-field experiences. The questionnaire (see appendix A) consists of three main sections:

- Definition, application areas and pro&con stakeholders
- Driving factors and objectives
- Constraints

The collected information was discussed and reviewed within periodic meetings with the members of ANIMP's Construction department. The next section presents a synthesis of the survey results.

Survey summary		
COMAPANIES INVOLVED	ROLES INTERVIEWED	NUMBERS OF INTERVIEWS
eni, Tecnimont, saipem, Techint, Technip, Rosetti Marino, Fagioli, Foster Wheeler	Engineering	4
	Procurement	2
	Construction	6
	Tendering	2
	Project management	5

Table 1.4 - Survey summary

1.3 Results

1.3.1 Definition, application areas and management stakeholders

In the first section of the questionnaire interviewees were asked to give their definition of modularisation, in comparison to four definitions taken from the literature. The definitions expressed by the interviewees, attribute to modularisation the subsequent common features:

- plant decomposition according to both constructability and process logic

- prefabrication of the modules in yards other than the construction site
- a need to satisfy transport and assembly requirements

A new definition has thus been proposed. The definition is supposed to include what was highlighted by the interviewees and therefore to effectively fit the EPC field. The proposed definition suggests that plant modularisation is:

"the decomposition of a plant in elements according to construction and process logic. These elements, or ***modules,*** *meet transportation and assembly criteria and are fabricated and tested in fabrication* ***yards*** *that differ from the construction* ***site****"*

The interviewees were also asked to choose, assigning a score from 0 to 100, possible areas emerged from literature where modularisation could be applied. The results are shown in Figure 1.3.

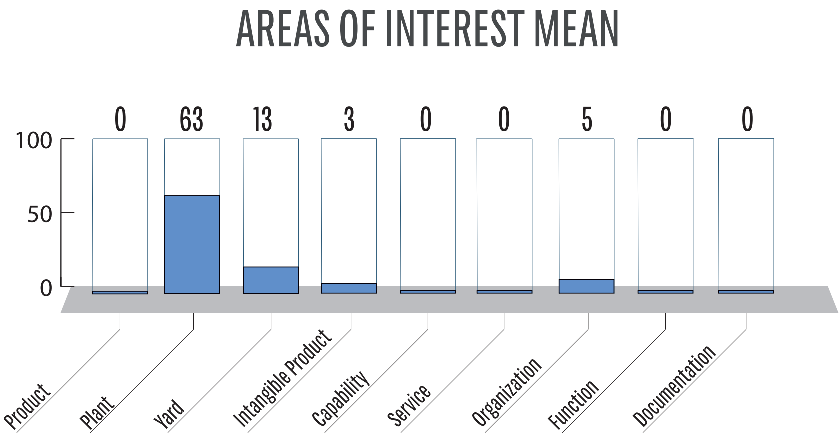


Figure 1.3 - Average weighted modularisation areas of interest

The main identified area of application for modularisation, is the "Plant"; it yielded an average score of 63/100, due to the critical impact of plant modularisation on the whole project. Beside this more than obvious result, it is interesting to observe that the second area of interest is the "Yard", with an average score of 13/100. This means that some of the interviewees testify the need for functional reconfigurability of the shipyard's areas. The need for a high degree of scalability in production capacity was also stressed. These yard's features have to be considered both as organisational principles for property yard and parameters that address the choice during the yard selection process. Other areas of interest like "Product", "Intangible Product", "Capabilities", "Service", "Organization", "Function" and "Documentation" yielded non-significant scores.

Figure 1.4 - Installation at site of a module fabricated by Saipem at Arbatax yard for a refinery in Suriname (By Fagioli)

The interviewees were then asked to indicate which internal/external stakeholders usually advocate for or against a modular approach. The Construction Department is by far the internal stakeholder more often identified as a modularisation "advocate". The interviewed sample attributed this fact mainly to the easier and safer construction activities enabled by modularisation. The internal stakeholder usually associated to stances adverse to modularisation, is instead the Engineering Department, due to the increased complexity associated with module design and a lack of confidence with the approach. Regarding the external stakeholders, the client is the one who usually takes the final decision whether modularise or not. He could be in favour or against modularisation, according with his identified priorities and objectives. Some of the interviewees stated that clients usually link modularisation to higher costs but faster delivery times. Local governments could be likewise for or against modularisation, mostly depending on the will to maximize the local content or otherwise minimize the social impact of construction activities at site.

1.3.2 Driving factors and objectives

In order to establish a priority ranking among factors that drive a project towards modularisation, the interviewees were asked to summarize them through an open-ended question, assigning a 0-100 weight to each of the mentioned driver. The drivers were then gathered under eleven main categories: Costs, Schedule, Site Conditions, Labour, Social/political, Safety, Constructability, Quality, Competitiveness, and Logistics.

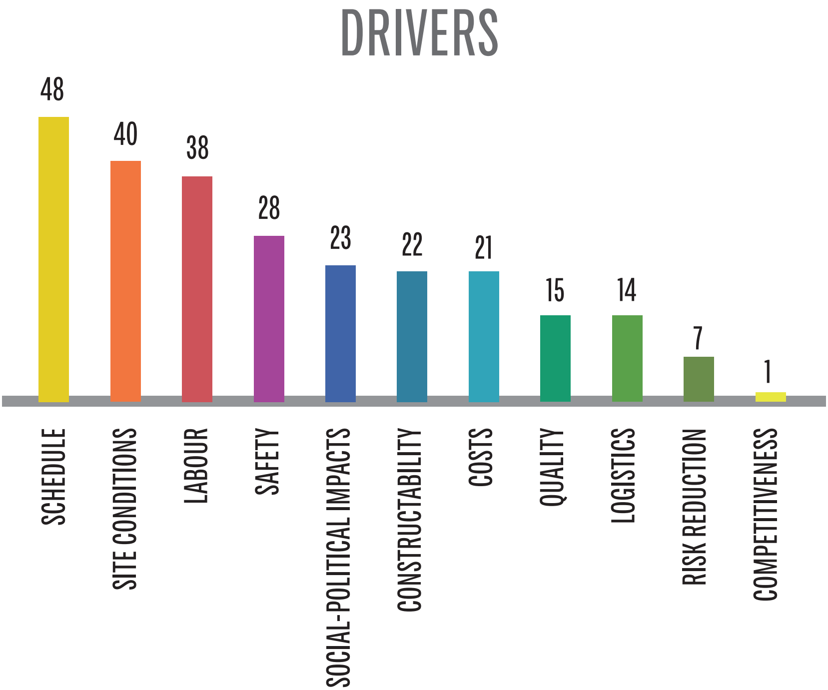


Figure 1.5 - Average weighted modularisation drivers

As shown in Figure 1.5 there are three modularisation drivers that yield an average score higher than 30/100:

» **Schedule:** with an average score of 48/100, schedule savings are recognized as the main driver for modularisation, especially when the customer is more focused on fast scheduling in lieu of cost containment. Most of the interviewees agree that this advantage could be achieved even if the circumstances presented in the literature review chapter do not occur. Schedule savings derive from the opportunity to allocate project construction workload to different fabrication yards. Furthermore, some of the interviewees state that modularity allows fully exploitation of the capabilities of subcontractors that can design and produce finite modules. Further time savings may be achieved by paralleling design and detail engineering activities. Last but not least, especially for packages that completely execute a specific function, some commissioning activities can be done in the yard, with obvious advantages in terms of time and money.

» **Site conditions:** this category includes weather conditions, site remoteness and security issues at site and received the second highest average score (40/100). Indeed, severe climate conditions for extended periods of time may hamper construction, introducing significant delays and cost increases, especially in locations with strict labour regulations (e.g. Alberta, Canada). Likewise construction sites located in highly dangerous and risky areas require a huge effort in site security and workers/asset protection. Site remoteness with its lack of infrastructure and adequate facilities to host expat workers, is also an important factor. Finally, site conditions are particularly important since they usually have indirect effects on manpower availability. Modularisation allows mitigation of the above criticalities, reducing the amount of work performed at

Figure 1.6 **- A view of the Horizon Oil Sands Plant, Fort Mc Murray, Northern Alberta, Canada. In the last decades modularization has been largely adopted in order to mitigate the impact of severe weather conditions at site (By Technip)**

site.

» **Labour:** The availability of low cost skilled manpower at site as well as an industrial area able to adequately support plant construction is a key factor for a successful project. The interviewees assigned an average weighted score of 38/100 to this driver. Remote site locations and areas with poor industrial development impose massive importation of expat workers, with the well-known issues in terms of costs and local content. On the other hand, areas characterised by intensive construction activities (e.g. Houston area) or disproportionate workers' wages (e.g. Australia), could make impossible to find available man power at reasonable costs. Modularisation provides effective solutions concerning these criticalities, allowing work to be shifted to areas where low cost manpower is largely available and yards or shops productivity rates are much higher. Interviewees point out that another relevant labour-related benefit of modularisation, is the reduction of the maximum number of workers simultaneously present at site, with positive

Figure 1.7 - One of the 160 modules fabricated in Thailand and then transported to Gladstone, Australia for the Queensland Curtis LNG project. Labor cost and skilled workforce availability are crucial drivers for the modularization of the recent Australian LNG plants (By Fagioli)

consequences in terms of site congestion, work efficiency, costs and resources utilisation balance within the company project portfolio.

The interviewed sample considers the enhanced **Safety** (average weighted score: 28/100) a medium importance driver for modularisation, since fabrication yards are usually safer and a more controlled environment than construction sites. Also, **Socio-Political factors** (average weighted score: 23/100) were found to be a relevant driver. Even medium size plants may indeed require thousands of workers simultaneously operating at site. This has serious implications on social fabric, especially in small countries or regions where the government requires projects to minimise the impact of construction activities on the local population. Also **Constructability**-related concerns, like layout constraints at site, yielded a significant average weighted score (22/100).

It is not surprising that "Costs", are only seventh in the drivers ranking. If none of the circumstances listed in paragraph 2 occurs, modularisation itself certainly implies higher costs in terms of structural steel, welding and transport costs. So what has driven our interlocutors to assign a 21/100 an average weighted score to "Cost" is that, in some specific scenarios, modularisation is the **only** feasible execution strategy. In an ideal world the stick built approach wins 'hands down' in terms of first cost. But in the real world, especially for challenging remote located projects, modularisation may be the only feasible strategy to reduce overall project costs.

Other drivers like **Quality, Logistics and Competitiveness** were less stressed by the interviewees.

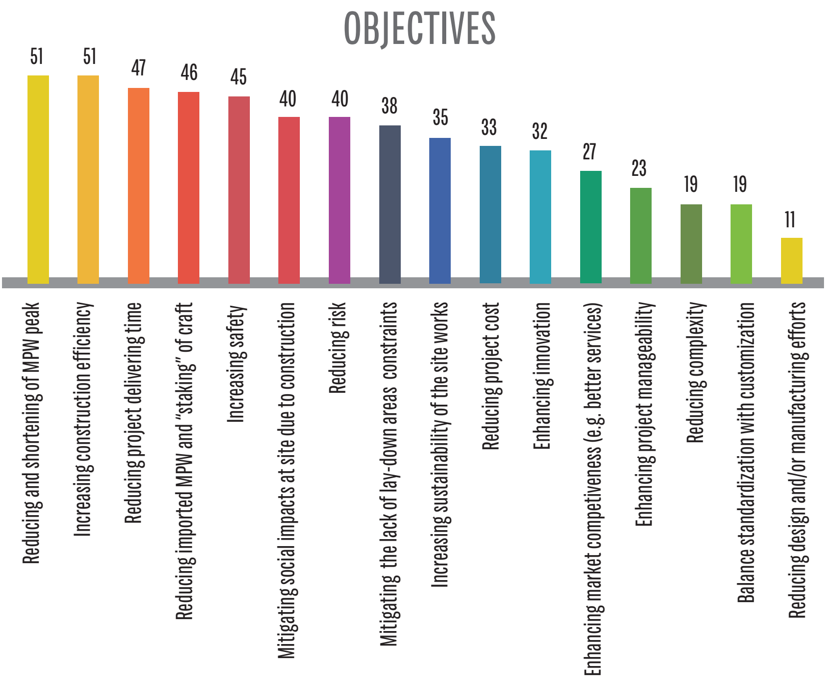


Figure 1.8 - **Average weighted modularisation objectives**

The interviewees were then asked to assign a weight to sixteen disaggregated objectives usually related to plant modularisation.

The analysis of the results illustrated in 1.8 confirms that the interviewees assign a primary importance to disaggregated objectives related to skilled manpower availability and cost, schedule reduction and site context issues.

1.3.3 Constraints

As for the drivers, the interviewees were asked an open question to list the major constraints associated to the adoption of a modular construction approach, assigning to them a score from 0 to 100. What emerged from the results, reported in Figure 1.9, is that there are three most relevant constraints:

- Module design issues
- Module transport issues
- Issues related to the higher complexity associated to modular projects

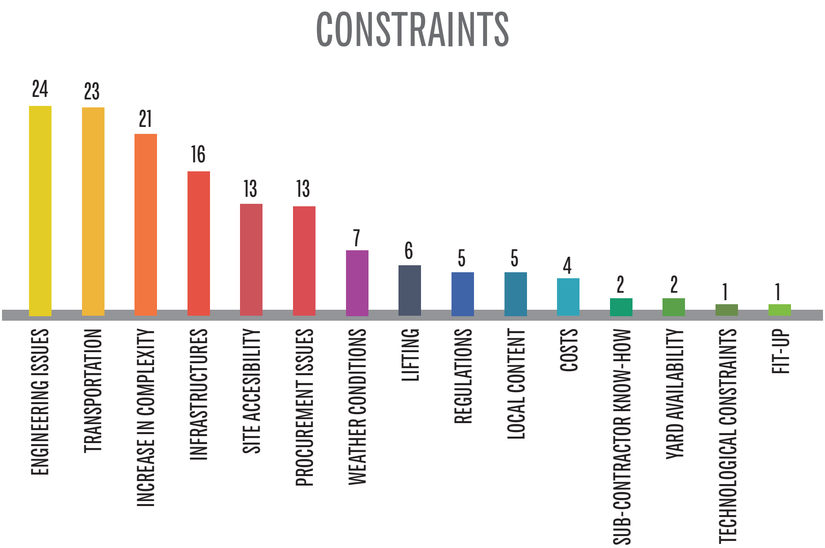


Figure 1.9 - Average weighted modularisation constraints

In regard to module **engineering issues** (average weight: 24/100), the need to provide the fabrication yards with the engineering deliverables as complete as possible and the opportunity to parallelise the construction activities with fabrication enabled by modularisation, induce an anticipation and a compression of the engineering phases which may not be easily manageable.

Furthermore, the need to accomplish the detail engineering as soon as possible on the basis of still significantly uncertain information may drive the adoption of a particularly conservative design approach, with obvious cost increases.

Also, it is possible that the module design itself implies constraints related to the plant complexity or to the lack of the designers' familiarity with a modular approach. Adopting this kind of approach for module design forces the engineering teams, in particular the detail engineering teams, on one hand to anticipate and reduce the delivery time of its deliverables; on the other hand detail engineering is also forced to work on the bases of partial information, which are subject to great uncertainties and feedbacks mainly relative to transportability, lifting and site accessibility analysis as a partial solution to this issue. Some of the interviewees identified, the opportunity to involve, from the very first phases of the engineering, a specialised module supplier, in order to lighten the work burden on the main contractor engineering department and in order to solve problems related to the main contractor not being familiar with module design.

Next, module **transport** issues (average weight: 23/100), are considered by the interviewees a major constraint. They have indeed a direct effect on module design. In particular, modules that

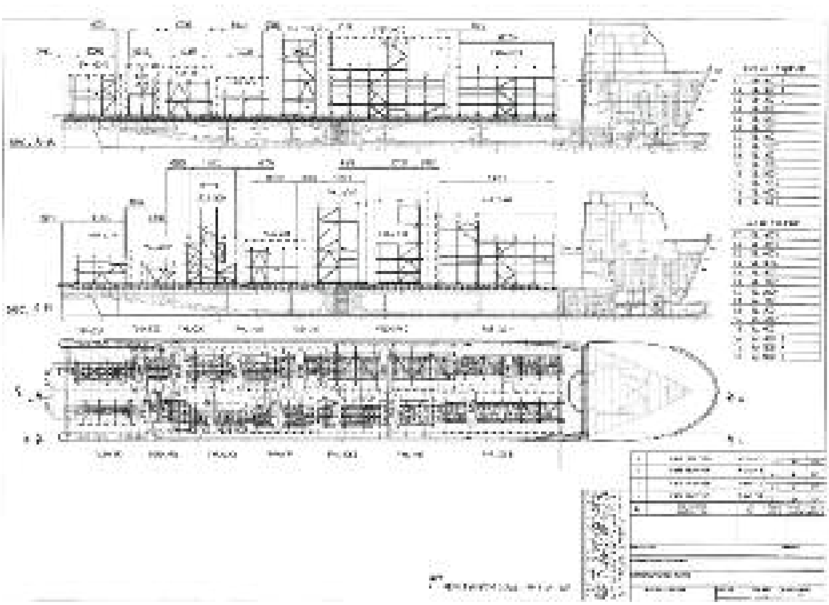


Figure 1.10 - Technical drawing of the stowage of modules produced in Italy and then transported by sea to South America. (By Fagioli)

need transportation by sea, are seen to require a design to deal with strong dynamic forces. So modules are usually provided both with bracings and structural reinforcements. The equipment disposition is aimed at maximising stability as well. This has consequences in terms of higher costs related to raw materials and increased design and welding activities.

Furthermore, carrying modules that can reach even 6000 tonnes requires the availability of extremely expensive transport systems and means that only a very limited number of carriers are able to tender. The size and weight of the modules make difficult the identification of viable transport routes, because of physical constraints, local regulations and the lack of adequate **infrastructures** (average weight: 16/100). This explains why a large portion of the respondents recognised the relevance of the lack of infrastructure. A proper selection of the fabrication yard should, therefore, carefully consider the means and the route to be used for the transportation of the modules from shop to site, identifying all the possible physical and regulatory constraints as well as any action needed to make transport feasible. It is not unusual that transport of the modules requires the construction or the adaptation of roads and bridges, with high costs even for a few miles. Interventions of this kind may also be required in order to enable the **accessibility** of the site (average weight: 13/100), such as the construction of docks suitable to download modules from the barges and the adaptation of construction site access roads.

The increased **complexity** related to the adoption of a modular approach (average weight: 21/100) is considered particularly relevant by the interviewees. From the project management standpoint, a situation where construction activities are divided between those carried out at the site and those at a fabrication yard , is reflected in duplicated planning and supervisory activities: the project is therefore characterised by a double schedule (the more yards involved, the higher supervisory effort required). This increase involves not only the EPC contractor but also the client

Figure 1.11 - **Module installation operation at two different sites in Canada**

company that may be forced to relocate its staff to multiple locations. Particularly critical is the transport planning activities. Errors in the estimation of module delivery time could lead to the means of transportation not being able to wait till delivery. This then would require rebooking of the transport systems which may not be available for several months.

Procurement activities (average weight: 13/100) are significantly affected by the adoption of a modular approach. This involves a further step in the supply chain, since materials and equipment must be first delivered to the yard and then transported (within modules) to the site. In addition, the need for parallelisation of the activities of engineering or even the possible outsourcing of such activities for specific modules, leads to a reduction in the volume of components bought from the same supplier, with obvious scale diseconomies. Some respondents also associate the parallelisation of engineering with a possible negative impact on the degree of commonality and standardisation of components within the different units of the system. Harmful effects on the costs of the components can also be caused by the aforementioned need to accelerate detailed engineering at the expense of accuracy in the purchase specifications and the possibility of a careful selection of suppliers. Finally, a factor of considerable complexity is the management of the module installation sequence. In fact, installation sequences that are not robust and flexible with respect to unexpected circumstances may produce situations in which the failure to complete a particular critical module causes the interruption of the construction activities. This could have severe repercussions on the delivery time of the project.

1.4 Discussion and improvement areas

One of the main results of the survey was to highlight the main gaps to be filled from a managerial and technical point of view in order to deploy the full potential of modularisation.

Analysing the survey results at an aggregate level modularisation emerges as an execution strategy that produces impacts of capital importance on each phase of the project.

Moreover, although the modular approach is already widely known by the main players in the EPC sector, a comprehensive and shared understanding of it within companies is still missing. The survey clearly highlighted some trends in the identification and prioritisation of constraints and drivers associated with modularisation, but the importance associated by respondents to these factors vary significantly. This is confirmed by the fact that the driver of greatest significance has an average weight of just 51/100. The most relevant criticality however gained an average weight equal to 24/100. This effect

Figure 1.12 - A modularised cold box for an LNG plant at Hammerfest, Norway . The unit, that had a weight of 2700 tons and was 60 meters high, was transported from Belgium to Norway by barge and then a semi-submersible ship. (By Fagioli)

can also be read as a substantial dependence of the interviewee's answer by the specific projects he/she had been involved in and obviously by the overall slight common view shared in the company.

From the EPC contractors' standpoint, plant modularity appears often to be a forced condition (maybe due to an explicit request of the client or by the boundary conditions of the project) more than a real strategic and operational decision. In this framework the Italian EPC sector needs to encourage the development and the diffusion of a modularisation culture, but at the same time to adopt managerial approaches that minimise the possibility of neglecting the fundamental principles of modularisation. The construction department is probably the most suitable stakeholder to promote and drive the consolidation of such a corporate culture.

According to this study, new project management approaches dedicated to modular projects have to be characterised by:

» Decision making tools that, from the earliest project phases, allow estimating, the suitability of a modular approach with regards to the fundamental dimensions of the project. Many of the interviewees declared that, making the decision whether to modularise or not "sooner rather than later", is crucial. For this reason the first constraint of such a decision making tool is the uncertainty of the data received as input. Perhaps the scoring model developed by CII (Construction Industry Institute[3]), may be considered an embryonic attempt to develop tools of this nature, but updates and improvements of this tool are hugely desirable, and what Saipem [4] developed for this purpose is definitively a step forward in this direction.

» New approaches to **engineering activities** that allow to exceed the vision of modularity just as a "partition" and splitting of a standard plant. Engineering activities customised for modularisation should indeed foster as much as possible the anticipation of modules' interfaces definition; both from a structural and functional standpoint. Feed-back loops existing between modules' design and transportability, lifting and site accessibility analysis have to be evaluated from the very first engineering phases. Process managers have to be involved to explore new technologies for module design enhancing functional completeness of each module. This could boost the commissioning activities at the fabrication yard, ideally resulting in ready for start-up modules. Also adopting golden weld approaches and precast foundations may result in minimized hook up activities.

» **Procurement** approaches able to not underestimate the increased complexity induced by modularisation, expressing a particular effort in the coordination with the Engineering department. Procurement and engineering departments should strongly cooperate in order to minimise the reduction of components commonality induced by modularisation. The definition of equipment and homologous components specifications that follows milestones shared by all the plant modules is also desirable. This would make possible to limit the negative effects on the amount of purchased components. Mitigating these effects is particularly complex when

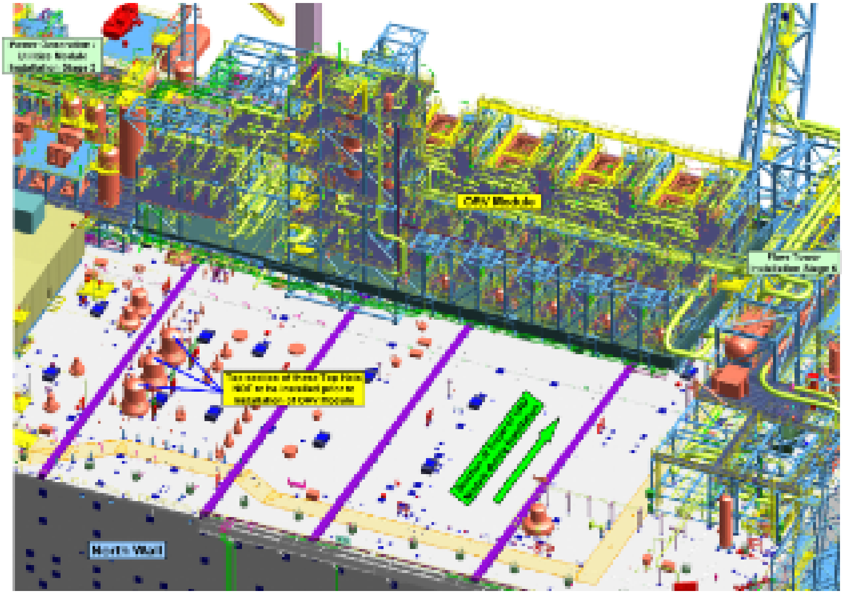


Figure 1.13 - 3D study of the installation of a 4800 tons module for a regasification terminal at Rovigo, Italy. (By Fagioli)

the the design and the manufacturing of parts or of all the modules are subcontracted. In this case a valuable strategy is following a centralised procurement as far as possible or at least strongly coordinated. The interviewees have different feelings regarding the best operational strategy for carrying out fabrication yards' Procurement. On the one hand it is argued that for simplicity reasons, construction activities should begin only once all the necessary materials and equipment for the modules production has been delivered. On the other hand someone prefers an approach where the module is assembled as soon as what is necessary to the fabrication of the structural elements becomes available.

A common point among the interviewed was the need to develop updated and comprehensive short lists of vendors and subcontractors holding the needed capabilities to provide both process packages and entire modules. Often the suppliers specialised in the fabrication of the main components or process unit within a skid/module, have no adequate capabilities to execute the entire module. Engineering and Construction departments should effectively support the procurement department in such mapping, especially during the evaluation of fabrication yards and not simply components vendors/suppliers.

(3) http://construction-institute.org/

» Improved **sequence of installation analysis.** As mentioned the delay of even a single critical module in the sequence of installation, may have such severe impacts to nullify the potential benefits of modularisation in terms of reduction of the delivery times. Flexible and robust installation sequences are crucial for a modular plant project, and arguably this factor should not be overlooked even in the plant layout design.

» Enhanced **project management and supervision tools.** The survey highlighted some perceived inadequacy of tools currently in use in addressing modular plant projects. Some project controllers highlighted the need to rethink the WBS and OBS templates generally used in the company, in order to distinguish two or more sets of activities: those performed at site and those performed at the fabrication yards.

» New **organisational structures:** the organizational structure of a modularised plant project has been deemed a critical success factor by the interviewee as it refers to complex work that is divided in various parts as first and then recombined. Automotive and , computer sectors have been on the cutting edge of modular studies, but the main principle can be applied to any type of business, independently from the dimension (large or small sectors).

Figure 1.14 - Panoramic view of a modularized refinery performed in Suriname. An accurate analysis of the installation's sequence of the modules is a key success factor for a modularized plant's project (By Saipem)

The first basic tenet of the modularization organization structure is that each stakeholder of the project is part of the business as a whole. Like modular furniture, each piece has a place and distinct purpose, but aimed at the same objective.

» Modularization projects are executed basically through three main type of stakeholders, i.e. the main contractor project management at the Home Office, the fabrication yard Contractors and the site erection contractor, that is the receiver of the produced modules. The equipment and Materials Suppliers are common to all Parties. To be effective, the Organization should foresee that each party is to stand strong its own, so that it can better support the business as a whole and execute the work together seamlessly. It means that organization and resources of the EPC Project Management Team should be self-governing at each modularization yard, i.e. it it should replicate the organization of the main project management team and have the resources and operating functions for managing its portion of the project and for dealing directly

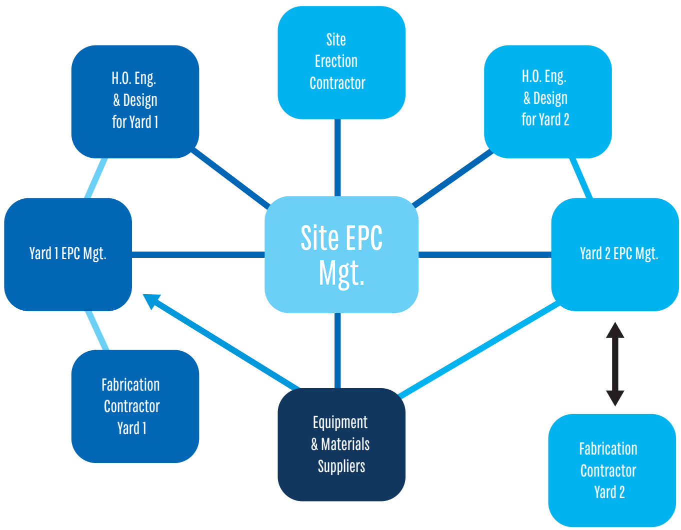


Figure 1.15 - **Modularized organizational structure**

with all parties involved in its own specific module, including material suppliers and home office Engineering team. The above organization structure has been recommended by almost all the interviewed construction people.

» Proper **contractual forms.** As it is known, the implied covenant of good faith and fair dealing is a general assumption that the parties of a contract will deal with each other honestly, fairly, and in good faith, so as to not destroy the right of the other party or parties to receive the benefits of the contract. This is implied in every contract in order to reinforce the express covenants or promises of the contract. Nevertheless, in some cases, conflicts still occur. When this occurs, a negative impact is suffered by the project, that in some cases could lead to disruptions and delays.

For reducing or hopefully avoiding the risk of the above conflicts, the contract should be fair but also and mainly it should fit the project configuration. Several type of Contract for implementing projects exist that, for sake of brevity, can be classified under two main categories, i.e. Lump Sum Turn Key (LSTK) and Reimbursable Contract (RC). The decision is the responsibility of the customer who, in taking the decision, should consider the significance of the area of uncertainties for the definition of the economics and time schedule, aiming to fairly share the risk of the project implementation. LSTK Contract could appear simpler to be managed by the customer, but it presents a higher risk of conflict in a modularization project compared with a stick built one. This is basically because of its rigidity which does not fit the complexity of the modularized project. It has been experienced that Reimbursable Contract fit the modularization project configuration better, given its flexibility as well as its sharing of risk between customer and main contractor.

The above considerations can be extended also to the fabrication contractor who are normally managed by the main contractor as a subcontract. In the case of the modularized project, the relative weight and the incidence of the fabrication contractor on the entire project does not make the subcontract the perfect tool for managing the work. A certain type of partnership, such as Joint Venture or Consortium, seems more suitable. Its definition should be consolidated since the time of the submission of the bid to the customer and should contain the share of the costs and schedule, so that the mutual interest of all the parties reduce the risk of conflicts.

Modularized project will be concluded successfully if a supply chain is built up between the main contractor, the fabrication contractor and the erection contractor.

Finally, the survey returned relevant output about possible tactical (short term) and strategic (long term) actions to support the optimal use of the modular approach. Some examples of this could be:

- The development of partnership and alliances with skilled manufacturers, involving them not only in the manufacturing but even in the module design. An important expected outcome of these partnerships is: a lighter workload on the main contractor's engineering department resources. Negative effects on procurement related to this increase in the subcontractors' contribution should be prevented, focusing on new and enhanced coordination tools (e.g. system engineering approches).

- The evaluation of investment opportunities in the fabrication yard site at strategic locations

As mentioned in 1.3.3, the survey has shown how the engineering design is one of critical factor for the implementation of a modular approach, because of not yet consolidated familiarity of the designers with this plant configuration. A further critical factor is represented by the transport and lifting impacts on structural aspects (and therefore on the project cost). This work identified and prioritized the main dimensions of modularity and outlined some areas of development for the full exploitation of the approach. In this light, in the next chapter problems and criteria related to module handling and transportation are reviewed. Furthermore, the study aimed to provide a technical contribution to overcoming some critical issues related to modules design as covered in the third chapter.

2 | Module handling and transportation

2.1 Module handling

Normally modules are land transported by Self Propelled Modular Trailers (SPMT) and loaded on to and unloaded from sea transport vessels; this can be done by lifting, using cranes aboard geared heavy lift ships, or by the Roll on – Roll off (Ro-Ro) method using SPMTs aboard barges or Ro-Ro ships. Tandem lifts may be possibly subject to structural design and/or use of spreader beams (special lifting devices between hook and module, i.e. beams to maintain lifting slings vertical and separated, to generate only vertical lifting forces in the module).

When very heavy, a module can be loaded / unloaded using skidding systems (skid ways + strand jacks or skid shoes for a more controlled operation).

All module transport, loading, sea transport and unloading operations are subject to review and approval of a Marine Warranty Surveyor (MWS), appointed by Client. The MWS's intervention is not required in the case of overland transportation.

Sea transportation plays a leading role in module delivery; in addition it needs special attention for the impact on the module technical characteristics. For these reasons the next paragraph will be focused on marine transportation criteria and operations.

2.2 Marine transportation criteria

The sea transportation of the modules produces critical cases regarding structural design, and thus requires detailed modelling.

At first, the adoption, to the possible extent, of standard module support arrangements is highly recommended, to simplify the grillage arrangements at all stages: in the fabrication yard, on the sea transport, in the storage area at site and onto foundations.

Temporary support arrangements for sea transport (to be removed when installed onto their permanent foundations) should be minimized, while foundations should be designed to enable modules to be directly delivered and placed upon foundations by SPMTs, possibly with no need for intermediate jacking arrangements.

The selection of sea transport vessel (ships / barges), the design of grillage, sea-fastenings and temporary support, as well as the integrity of the module structures themselves must comply with the Project Design Criteria and are usually subject to review and approval by an independent MWS appointed by Client.

2.2.1 Sea motion criteria, grillage and seafastening design

The cargo, the internal reinforcement of the cargo, the sea fastenings, the grillage and the vessel must be designed to withstand the motions and forces resulting from the design transportation conditions.

Design motions may be derived by means of dynamic response analyses or from model testing.

In all cases, a realistic combination of environmental loads and wave directions, representing bow, quartering and beam sea conditions should be used. If neither motion simulations nor model tests are performed, in case of standard configurations and under satisfactory marine procedures, the default motion criteria may be acceptable.

The Guidelines by the Warranty Surveyors (DNV, Noble Denton, RINA, IMO, etc...), provide the default motion criteria with reference to the sea transport route and to the design sea state.

As a reference, an example of motion criteria for the definition of the Ships / Barges harmonic motion, are listed below (ref. GL Noble Denton - ND/0030 – Guideline for Marine Transportation):

- Roll amplitude 20°;
- Pitch amplitude 10°;
- Vertical acceleration 0.2g;

The standard criteria ND/0030 shown above should be applied in accordance with the following:

- The roll and pitch values listed above should be assumed to apply for a 10 seconds full

NATURE OF TRANSPORTATION	CASE	LOA (m)	B [1] (m)	L/B [1]	Block Coeff	Fully cycle period (secs)	Singleamplitude Roll	Pitch	Heave
Unrestricted (these values to beused unless any of the following apply)	1	> 140 and > 30		n/a	< 0.9	10	20°	10°	0.2 g
	2	> 76 and > 23		n/a	any	10	20°	12.5°	0.2 g
	3	≤ 76 and ≤ 23		≥ 2.5	< 0.9	10	30°	15°	0.2 g
	4				≥ 0.9		25°		
	5	≤ 76 and ≤ 23		< 2.5	< 0.9	10	30°	30°	0.2 g
	6				≥ 0.9		25°	25°	
Weather restricted operation in non-benign areas for a duration <24 hours (see Section 7.9.2 d). For L/B < 1.4 use unrestricted case	7	any		≥ 2.5	any	10	10°	5°	0.1 g
	8	any		< 2.5, ≥ 1.4	any	10	10°	10°	0.1 g
Weather restricted operation in non-benign areas[2] (see Section 7.9.2 e). For L/B < 1.4 use unrestricted case	9	any		≥ 2.5	any	10	5°	2.5°	0.1 g
	10	any		< 2.5, ≥ 1.4	any	10	5°	5°	0.1 g
Inland and sheltered water transportations (see Section 7.9.2 f). For L/B < 1.4 use unrestricted case	11	any		< 2.5, ≥ 1.4	any	Static	Equivalent to 0.1 g in both directions		0.0
Independent leg jack-ups, ocean tow on own hull. For L/B ≥ 1.4 use unrestricted Cases 1 to 6	12	n/a	> 23	< 1.4	n/a	10	20°	20°	0.0
Independent leg jack-ups, 24 hours or location move. For L/B ≥ 1.4 use unrestricted Cases 7 to 8 as applicable	13	n/a	> 23	< 1.4	n/a	10	10°	10°	0.0
Mat-type jack-ups, ocean tow on own hull. For L/B ≥ 2.4 the pitch angle may be reduced to 8°	14	n/a	> 23	< 1.4	n/a	13	16°	16°	0.0
Mat-type jack-ups, 24 hours or location move	15	n/a	> 23	n/a	n/a	13	8°	8°	0.0

Table 2.1 - **Default Motion Criteria - ref. GL Noble Denton - ND/0030 – Guideline for Marine Transportation**

cycle period of motion;

- The roll and pitch axes should be assumed to pass through the center of floatation of the sea transport ship
- Phasing shall be assumed to combine, as separate load cases, the most severe combinations of:
  - roll ± heave
  - pitch ± heave

Alternative default motion criteria may be acceptable as provided, for example, in DNV Rules for the Classification of Ships, January 2003, Part 3, Chapter 1, Section 4, Ref. [12], or IMO Code of Safe Practice for Cargo Stowage and Securing, 2003 Edition, Section 7, Ref. [16].

For the Grillage, Seafastening and Cargo Design, the load components during transportation to be considered when analyzing the total forces acting on the cargo, the vessel and grillage and sea fastenings are those due to:

- The static weight of the cargo;

- The dynamic loads which result from the vessel rigid-body motion in all six degrees of freedom;
- The static component of weight which acts parallel to the vessel deck when the ship rolls or pitches;
- Wind load;
- Ballast distribution in the vessel.

Regarding the loads due to the motions above, the combination of motions that gives the highest loading in any direction must be considered. If more detailed information is not available (such as a dynamic analysis taking account of phase relationships to compute acceleration vectors), the highest loadings resulting from the following motions is combined as two separate load cases:

- Roll, heave and sway
- Pitch, heave and surge

Loads may normally be calculated using the assumption that all motions can be approximated by sinusoidal functions.

Alternative method is provided by RINA (Rules for checking the arrangement intended for sea transportation of Special Cargo); the Guideline provides the equations to calculate the accelerations a_x,a_y,a_z in the generic point x,y,z and the relevant loads F_x,F_y,F_z, under the known hydrostatic data of the ship / barge. In this case the loads already include the static component of weight which acts parallel to the vessel deck when the ship rolls or pitches.

Structural loading due to green water impact should not be assessed and it will be assumed that ship selection and/or direction of stowage on the modules on the ships decks will avoid cargo overhang, and thus the possibility of cargo immersion.

The grillage and sea fastenings has to be designed in accordance with a recognized standard or code of practice. Wherever possible, the design should be carried out based on the requirements of one code only.

The sea fastening shall be designed in order that the static stresses in all members do not exceed the allowable stresses in accordance with AISC (American Institute of Steel Construction) Manual or other acceptable code. In some case it is allowed to exceed the standard allowable stress according to applicable recognized International Standards.

The grillage design and layout should take account of any limitations imposed by the load-out method, for example the set-down height and width of the SPMTs.

The design of the grillage must be based on the loads derived from the vessel motions as defined above. The relative stiffness of the ship's frames and bulkheads shall be taken into account. The effects of superposition of loads shall be accommodated in the design when welds/connections are

Figure 2.1 - Load-in operation of modules at port from RoRo vessel and transfer on barge to reach final location at site one by one (By Saipem)

made between the grillage and ship's deck following load-out.

The purpose of the sea-fastenings is to secure the cargo during the voyage so that neither the cargo nor ship suffers damage as a result of the loadings derived from the ship motions caused by the design environment conditions. Primary sea-fastenings shall be designed to be removed easily without damage to the cargo. During and following the removal of primary sea fastenings, adequate residual sea-fastening shall remain to safely restrain the cargo until its removal from the ship.

Relevant to Cargo Strength, modules need to have adequate structural strength to be transported without damage from the maximum loadings resulting from the unit's motions under the design environment. Modules shall be generally analyzed as a three-dimensional elastic space frame, including appropriate constraints to represent the grillage and sea-fastening support points. The structural model shall include all primary and secondary members and may take account of the shear stiffness of floor decking, if appropriate.

In addition to this global analysis, local analysis may also be required with a twofold purpose: to quantify load effects in localized highly loaded locations (e.g. grillage support or sea-fastening connection points) and to confirm the adequacy of equipment support frames and saddles and the connection of such items to the primary module members.The module fabricator operating at the module assembly site should provide and install sufficient wood covers and plastic wrap / tarpaulins as and when required, to ensure protection of the module and its components against the severity of sea transportation conditions, in accordance with the project Preservation Procedures (based upon manufacturers' requirements for equipment)

2.2.2 Sea transportation vessels load-out and load-in

Self-propelled vessels can be planned for the transportation of plant modules: they can be either geared heavy lift ships (capable of self loading and discharge), or flat deck open stern type module carriers, capable of handling modules across their sterns.

Alternatively barges with tugs can be used. In case of barges or RoRo vessels, loading and unloading ops by SPMTs or by skidding system should be used.

The ship (or barge) shall be classed by a recognized IACS (International Association of Classification Societies) Member. The loads induced during loadout, including longitudinal bending, loads on internal structure and local loads, shall be checked to be within the approved design capabilities.

Mooring attachments and all attachments for jacking or winching shall be demonstrated to be adequate for the loads anticipated during or after load-out.

Ship stability should be shown to be adequate throughout the load-out operation. Particular attention should be paid to:

» A load-out onto a ship with a small metacentric height, where an offset centre of gravity may induce a heel or trim as the structure transfer is completed – i.e. when any transverse moment ceases to be restrained by the shore skidways or trailers.

» A load-out where there is a significant friction force between the barge and the quay wall, contributed to by the reaction from the pull on system and the moorings. The friction may cause 'hang-up' by resisting the heel or trim, until the pull-on reaction is released, or the friction force is overcome, whereupon a sudden change of heel or trim may result.

» Cases where a change of wind velocity may cause a significant change of heel or trim during the operation.

After the module is fully on the ship, then stability should comply with the MWS's requirements for marine transportations, and those of contractual technical specifications and ship's owner. As a general rule, the minimum ship freeboard during load-out should be 0.5 m plus 50% of the maximum wave height expected during the load-out operation.

The bundling of openings in the ship's deck shall also be considered for low freeboards.

The strength of the load transfer bridges or ramps should be demonstrated. Ramps shall be checked for loads induced by ship moorings and movements and load transfer forces induced by SPMTs or skidding system.

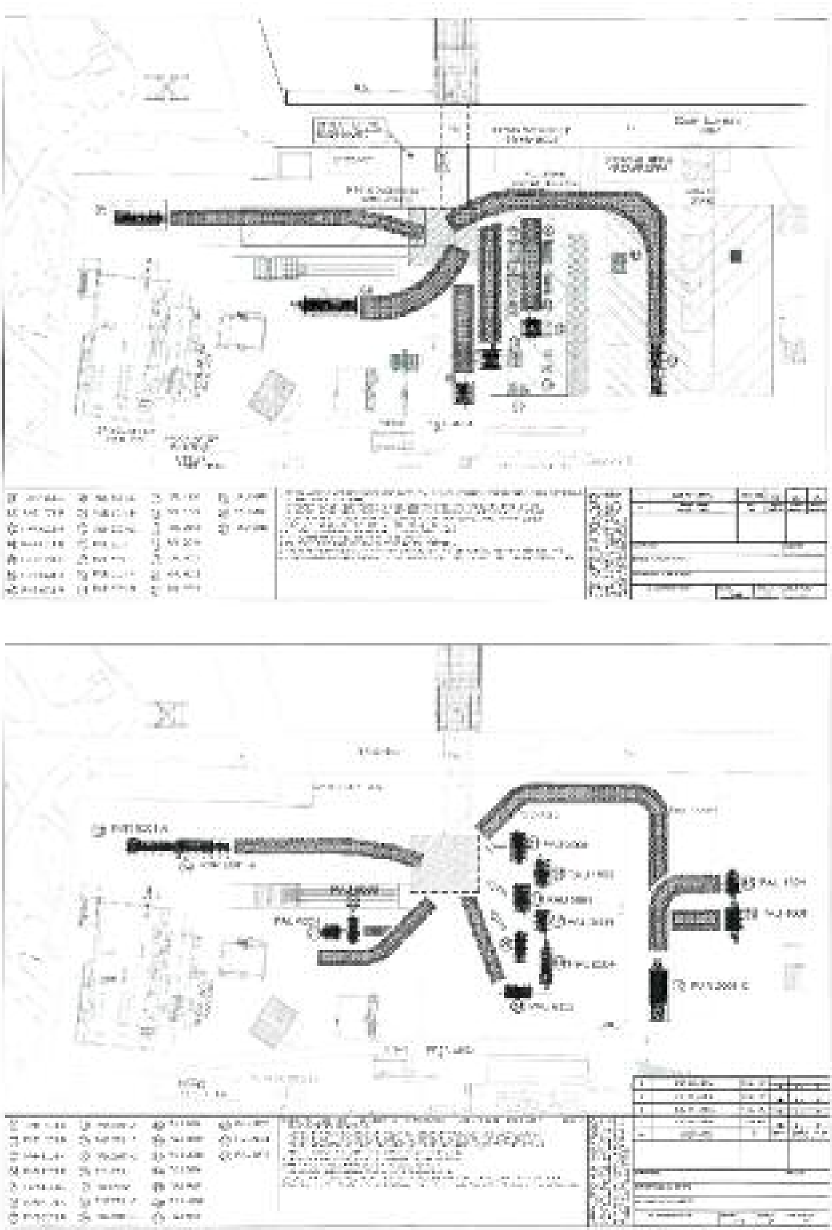


Figure 2.2 - **Technical drawings of the loading area in a fabrication yard**

Tolerances on ramp movement should be evaluated to be suitable for anticipated movements of the ship during the operation. Where a ship, due to tidal limitations, has to be turned within the loadout tidal window, the design of the ramps should be such that when the loaded unit is in its final position they are not trapped, i.e. they are free for removal. Suitable lateral guides have to be provided along the full length of ramps.

Sufficient articulation or flexibility of SPMTs should be provided to compensate for level and slope changes when crossing from shore to ship and vice versa. Calculations shall show that the load is fully borne by the SPMTs as in the design case, without overstressing the module structure, especially if the load transfer is between two floating vessels, such as between a ship and an intermediate bridge barge arrangement.

The line and level of the ramp and SPMTs shall be documented by dimensional control surveys and reports as necessary for load control. The line and level have to be within the tolerances defined for the loadout operation and design. For floating loadouts care shall be taken to ensure that minimum friction exists between the ship and quay face. Where the quay has a rendered face, steel plates shall be installed together with the ship fendering system. The interface between the ship and ship fendering shall be liberally lubricated with grease or other substitute which complies with local environmental rules.

A loadout is normally considered to be a weather restricted operation. Limiting weather conditions for the loadout operation shall be defined, taking into account:

- the forecast reliability for the area
- the duration of the operation including a suitable contingency period
- the exposure of the site
- the time required for any operations before or after the loadout operation including ship movements and moorings, ballasting, system testing, final positioning and initial seafastening
- currents during and following the operation, including blockage effects if applicable
- the wind area of the cargo and the vessel.

Marine Warranty Surveyors (MWS) typically define load-out and offloading operations in classes according to the tidal conditions. Requirements for design, reserves and redundancy of mechanical systems will vary according to the class of load-out.

According to Noble and Denton (ref. GL Noble Denton 0013/ND Rev 7 - 22 June 2013 - Guidelines for Load-Outs) the Class Tidal limitations are the following:

1. The tidal range is such that regardless of the pumping capacity provided, it is not possible to maintain the ship level with the quay throughout the full tidal cycle, and the loadout must be completed within a defined tidal window, generally on a rising tide.

2. The tidal range is such that whilst significant pumping capacity is required, it is possible to maintain the ship level with the quay during the full spring tidal cycle, and for at least 24 hours thereafter.

3. Tidal range is negligible or zero, and there are no tidal constraints on loadout. Pumping is required only to compensate for weight changes as the loadout proceeds.

4. Grounded loadout, with tidal range requiring pumping to maintain ground reaction and/or ship loading within acceptable limits.

5. Grounded loadout requiring no pumping to maintain ground reaction and/or ship loading within acceptable limits.

Modules shall be designed taking into account static and dynamic loads, support conditions, environmental loads and loads due to misalignment of the sea transport vessel and quay or uneven ballasting. For SPMT loading and offloading, the reactions imposed by the trailer configuration shall be considered. For lifted load-outs, the structure, including the pad-eyes, shall be analyzed for the loads and reactions imposed during the lift.

The load-out of the quay, quay approaches, wall and foundations have to be demonstrated to the MWS as being adequate for the loads to be transferred. This can be in the form of historical data for loading quays. The Marine Offloading Facility (MOF) shall be designed for handling heavy loads by SPMTs or skidding.

A statement shall be submitted showing the capacity of all mooring bollards, winches and other attachments to be used for the load-out.

Compatibility between quay strength and elasticity, and the support conditions used for analysis of the structure, shall be demonstrated as appropriate.

Bathymetric information for the area covered or crossed by the barge during load-out, post-load-out operations and sail away shall be supplied. Under keel clearance shall not normally be less than 1.0 m during the period for which the ship is in load-out position. This may be relaxed to 0.5 m, subject to confidence in the lowest predicted water levels, and provided that a check of the load-out area has been made by bar sweep, divers' inspection or side-scan survey; these investigations should be sufficiently recent to represent actual conditions at the time of load-out.

Where there is a risk of debris reducing under keel clearance, a sweep shall be made immediately prior to the ship berthing to ensure that no debris exists that could damage the barge keel plating. The results of the sweep shall be confirmed by further soundings check around the ship perimeter after ship berthing. For tidal load-outs, an easily readable tide gauge shall be provided adjacent to the load-out quay in such a location that it will not be obscured during any stage of the load-out operation. Where the tide level is critical, the correct datum should be established.

In additional to MWS approval, port or other competent authority approval for the operation should be obtained, and the required control of marine traffic instituted.

2.3 Transportation by SPMTs

Self-Propelled Modular Trailer (SPMT) are multi-axle trailers designed for the transportation of large and heavy cargoes. SPMTs are designed in modular construction and can be coupled side to side and end to end, or remote units can be operated as a single trailer via radio controls. A SPMT consists of a very strong and rigid chassis, which also acts as a load-carrying platform to which wheel bogies are attached in pairs, to form the required length of transport. Each wheel bogie consists of two rubber-tyre wheels and is rigidly fixed to the chassis by a hinged elbow joint, which is supported on hydraulic rams. This hydraulic ram acts as the suspension for the SPMT and also provides the lifting capability. Attached to the end of the SPMT is a Diesel driven power pack, which provides hydraulic power to the various functions of the SPMT.

The SPMT is propelled by hydraulic drive motors, which are mounted on its axles. Hydraulic power is supplied to each of the drive motors by a pump on the power pack and speed is controlled via a remote hand operated portable console. Forward and reverse travel is achieved by reversing the flow of hydraulic oil to the drive motors. Speed of the driven axle is controlled by

Figure 2.3 - The 25 meters deck of an offshore plant on a Self-Propelled Modular Trailer (By Fagioli)

flow regulators, which prevent the occurrence of over-speed of the wheels. Normal operating speed of the SPMTs is 5 km/h, but may vary depending on the load and configuration.

The steering of the SPMTs offers major advantages over other forms of conventional hydraulic trailers. The steering is controlled by electro-hydraulic motors rather than by a series of mechanical steering rods. Each of the axles of the transporter moves independently and is monitored and controlled by the computerized control system. This offers total flexibility of steering options with each wheel bogie able to swing through 260° (130°). The position of each wheel is controlled electronically through the remote operations console and nine steering programs are available. The electronic steering control can be used for a group of two or more SPMT's to ensure that all wheel bogies of all the transporters act together and turn about a single point.

Systematic and controlled pumping of hydraulic fluid into or out of each suspension can raise or lower the transporter bed +300 mm from the normal running height of 1500 mm

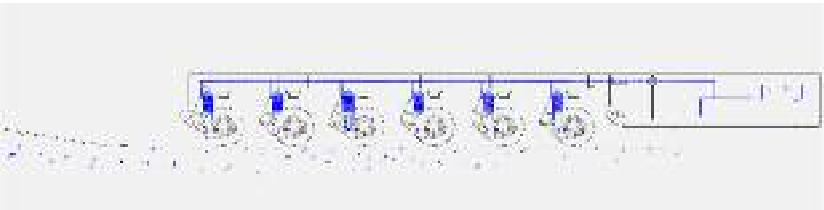


Diagram 2.1 - A hydraulic cylinder supports each of the wheel bogies. The cylinders on each bogie can be linked hydraulically to the other wheel bogie cylinders to form groups (Diagram 2.1).

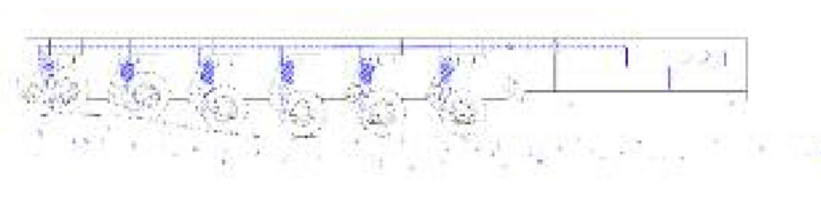


Diagram 2.2 - This allows free flow of hydraulic fluid between each hydraulic ram allowing the SPMT to negotiate uneven ground, cambers and gradients whilst maintaining equal loading in each hydraulic ram within that group (Diagram 2.2).

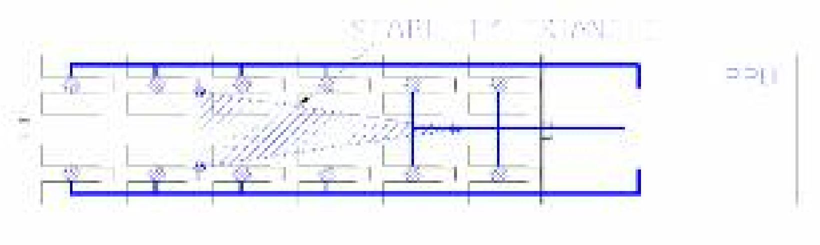


Diagram 2.3 - **Linking all hydraulic rams on a single trailer would result in an unstable transporter bed with no control. The SPMT is normally split hydraulically into three separate hydraulic groups (leading to a three-point suspension) that can be controlled individually from the main power unit (Diagram 2.3).**

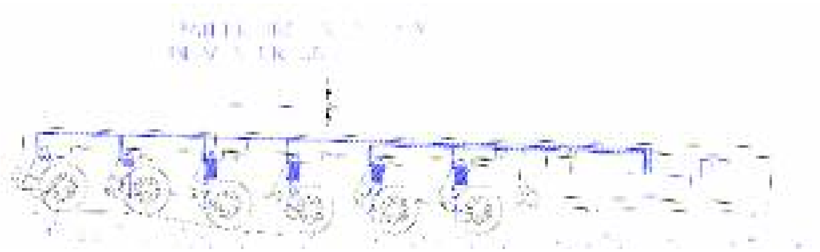


Diagram 2.4 - **As the SPMT's negotiates uneven ground, cambers or gradients, the hydraulic fluid will free flow within each suspension to maintain equal loading within each suspension group (Diagram 2.4).**

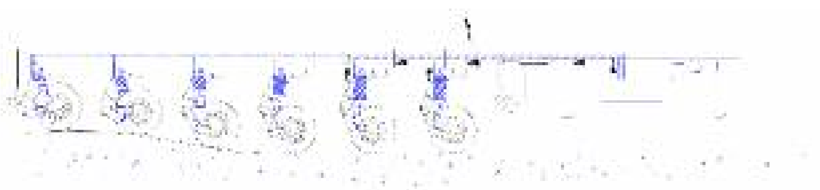


Diagram 2.5 - **Additional hydraulic fluid can be can be pumped from the Power Unit (PPU) into or out of each cylinder group to adjust the level of the SPMT (Diagram 2.5).**

Control of the elevation of the transporter is through the hand operated remote console. Safety valves protect the hydraulic circuit so that the transporter platform does not collapse in the unlikely event of hydraulic failure.

Modules are land transported by SPMTs and loaded on to and unloaded from sea transport vessels by the Ro-Ro method using SPMTs. The load-out path shall be freshly graded prior to load- out, pot holes filled and compacted, debris removed and obstructions to the load-out path identified and removed. Where a structure cannot be loaded out directly onto a barge or vessel without turning, turning radii shall be maximized where possible. For small turning radii, lateral supports and restraints shall be installed between the trailer and the structure, load-out frame and cribbage. It is possible (and is often the case) that a site move may be part of the load-out operation.

Maximum axle loading shall be shown to be within the trailer manufacturer's recommended limits. 'Footprint' pressure on the quayside, linking ramp and ship's deck shall be shown to be within the allowable values. Shear force and bending moment curves shall be prepared for the trailer spine structure, and maximum values shall be shown to be within the manufacturer's allowable figures. Linking ramp capacity shall be demonstrated by calculation and these calculations shall form part of the load-out procedure.

In general, hydraulic systems should be linked or balanced as a three point hydraulically linked system to provide a statically determinate support system, thus minimizing torsion on the structure. In all cases the arrangement shall be compatible to the support assumptions considered for the structural analysis of the structure being loaded out. A contingency plan shall be presented to cover potential hydraulic leakage or power pack failure. Stability of the hydraulic system to resist overturning shall be shown to be adequate, particularly when a 3-point hydraulic linkage system is proposed. The centre of action of the structure (Center of Gravity COG) shall remain within the middle quarter of the trailer support base, taking into account any uncertainty in:

1. the horizontal and vertical centre of gravity, with the adequate contingency factors and the COG envelope;

2. the design wind speed and relevant design wind load;

3. any inclination of the structure/trailer assembly on shore (slope and operational out of verticality);

4. the predicted inclination of the barge under the design wind and under the ballast operation (load out/in cases);

5. SPMT's acceleration and emergency braking for an emergency stop;

6. possible change of heel or trim due to the ballast operation during Ro-Ro phase and due to the release of hang-up between the barge and the quay, and any free surface liquids within the structure.

Whilst a 3-point linkage system results in a determinate support system, a 3-point support system is generally less stable than a 4-point support system. Stability for both 3 point and 4 point support systems shall be documented.

3 | Structural design aspects: a case study

3.1 Introduction

As illustrated in previous chapters, there are several structural design aspects which can affect the feasibility and affordability of modularization. Within a simple cost-benefit framework, they can be summarized as follows.

“Direct” costs

- Larger structural cost (material/weight, detailing, etc) due to additional loading conditions (transportation, lifting, etc)
- Transportation costs
- Need for larger installation means (cranes, etc)

“Indirect” costs

- More complex structural design
- Need to complete structural design in a shorter time
- Need of early interface with transportation/lifting contractor

“Direct” benefits

- Reduction in the on site construction cost
- Reduction of risks associated to onsite construction

- Reduction of project delivery time

"Indirect" benefits

- Better performance (e.g. in terms of stiffness) of the modularized structure
- Better durability (reducing maintenance)
- Better flexibility with respect to overall equipment life cycle (future XXXX revumpings and renewals)

In order to investigate such aspects, a typical pre-assembly (pipe rack) taken from a real application has been studied. Several aspects of the design have been considered and some possible improvements have been proposed. Within the above cost-benefit framework, the following three main targets have been identified.

1. Reduce weight

To achieve this goal, two main areas of intervention can be explored:

(a) classical **structural optimization,** which can be obtained both by varying the structural layout and by working on structural element sizes while preserving the layout. The first option can easily conflict with the equipment layout and for this reason has been disregarded here. The second has been pursued, even though code constraints of existing code provisions often hinder this type of optimization process.

(b) **reduction of loads,** which can be obtained either by adopting more sophisticated analysis procedures or by adopting design solutions which are rewarded by the code with a more favorable load level, the latter being typically the case of seismic loading; both options have been investigated in this study.

In particular, the working group has extensively studied the theme of a more realistic representation of various loading conditions for modular structures. However, reduction of loads coming from the equipment (weight, operation and thermal effects) has not been attempted, even though some considerations have been made on the action due to PSVs (Pressure Safety Valves); furthermore, activities regarding transportation loads has just begun, with special reference to standard barges operation, so that no result are presented in this report .

2. Introduce standardization/versatility

Standardization is the key for addressing the need for a more complex design to be performed in a shorter time (see the above "indirect costs" list); in this light, standardization can be related either to the actual structure or to the design process itself. It can be argued that it is practically impossible to standardize civil structures given the wide spectrum of loading combinations that are to be applied according to equipment, seismicity, wind conditions, transportation etc. In this context, standardizing a structure means to make it easily adaptive (versatile) to loading conditions of increasing level, e.g. by simply adding some structural elements and/or modifying a limited number of existing ones.

3. Improve functionality

All the items in the "indirect benefit" list can be seen as contributions to the functionality of the construction, i.e. the capability of fulfilling, in a more efficient and economical way, the needs for which it has been designed.

3.2 General issues

A single case study has been analysed in this first year of activities, regarding a typical pipe rack structure (whose structural layout is depicted in Figure 3.1): the main findings and proposals resulting from the analysis will be summarised in the Appendix. Here, however, an attempt is made to draw some general considerations for a wide class of industrial buildings, i.e. open steel frames carrying equipment, characterised by:

» rectangular, or close to, structural plan, often showing significant elongation;

» need for an open transversal section;

» irregular vertical spacing of horizontal beams;

» lack of well-defined horizontal levels, both for the absence of flooring systems and for the vertical offset between beams running in the two directions;

» lack, in many cases, of an efficient horizontal bracing system connecting the vertical frames;

» strict requirements for fire resistance;

» high degree of transparency against wind actions.

3.2.1 Weight reduction: welded joints vs bolted joints

As already mentioned in the introductory remarks, the structural optimization for weight reduction is often prevented by strict requirements, connected to stiffness and/or bearing capacity of the considered structures. Nevertheless, some improvement in the overall weight can be achieved by

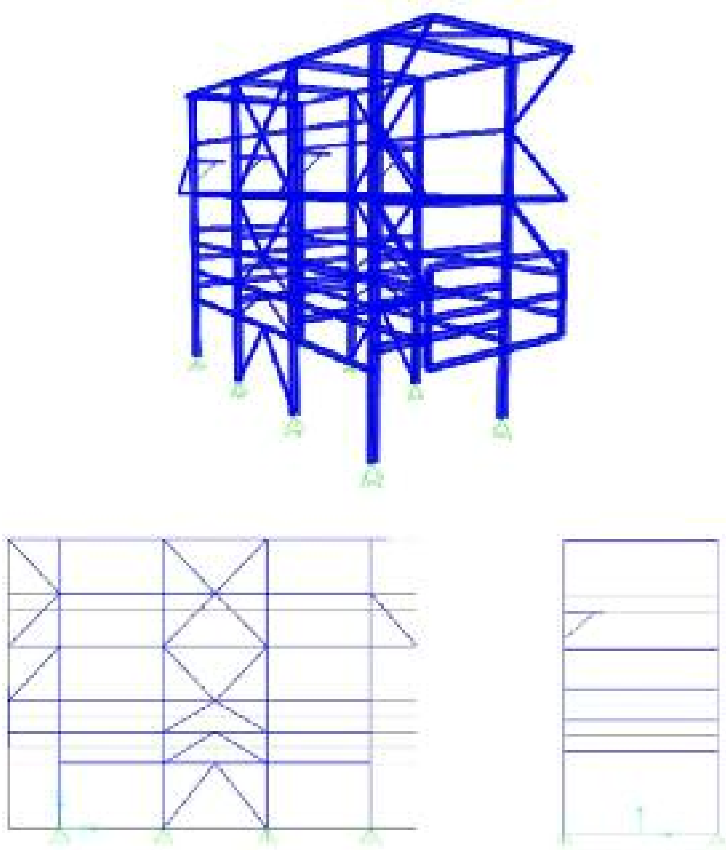


Figure 3.1 - **Structural layout of the case study considered in this chapter: general view (top), longitudinal frame (left bottom), transversal frame (right bottom)**

considering welded joints instead of bolted connections.

Welded joints are obtained by suitably combining several welds on different parts of the structural elements. By comparing welded and bolted joints, one finds that the former show several advantages: 1) "natural" monolithic behavior of the joints; 2) higher stiffness with a limited adoption of additional members; 3) simpler layout, with the consequence of additional freedom in the structural design. All these features might entail a reduction of structural weight, particularly because connecting plates and packing plates, which are commonly adopted in bolted connections, are not necessary in welded joints. As a rule of thumb, in the case of steel frames like the module considered herein, the impact of plates and bolts on the overall weight may easily reach 10%.

On the other hand, welded connections are characterised by some critical issues, mainly connected to the possible presence of defects (cracks, lamellar tearings, inclusions, etc.). For this reason, it is compulsory to investigate the accuracy of welds by means of non-destructive techniques. It seems that the testing task can be reasonably handled in the case of modular structures, which are mostly assembled in the workshop: in such a controlled environment, non- destructive analyses can be carried out in an easier way.

3.2.2 The determination and treatment of wind actions

The design of the structure in the case-study module against wind effects was performed within the framework of Eurocode 1- part 4 [8]. Accordingly, loads are given as static forces depending on the site design wind (average velocity and turbulence), on the system aerodynamics and on a structural coefficient. No attempt was made to reduce loads working on the first two aspects; coming to the structural coefficient we recall that it takes account of the dynamics effects, which increase the response, and of the non-simultaneous occurrence of peak pressures over the exposed structure, which has a beneficial effect.

The choice of a unit coefficient, which is an usual option and was made in the original design, is based on the assumptions that the two effects cancel each other; thus, in order to reduce the wind loading, the dynamic behaviour must be improved and/or spatial correlation effects, responsible for non-simultaneous pressure peaks, must be better exploited.

For usual structures, the first aspect is related to the increase in lateral stiffness, which was a general objective of the case study. In addition, some work has been done on the spatial correlation effects, both on the structural coefficient approach and by a more refined technique based on complete dynamic analysis. Some encouraging results have been obtained but it is deemed that the topic could deserve a more substantial research effort; in this perspective the performance of a test campaign in the wind tunnel could be evaluated.

3.2.3 Stiffness: horizontal bracing as a prototype problem of code application

The introduction of horizontal bracing, at least on top of the structure, improve the overall structural behaviour in many respects, leading to a more effective collaboration among transversal frames which results, in turn, on a favourable internal force redistribution for the cases of transversal loading (e.g. wind or PSV operation). In addition, it must be quoted that Eurocode 8 Part 1 [9] states, among the "Basic principles of conceptual design", the following:

4.2.1.5 Diaphragmatic behaviour at storey level

(1) In buildings, floors (including the roof) play a very important role in the overall seismic behaviour of the structure. They act as horizontal diaphragms that collect and transmit the inertia forces to the vertical

structural systems and ensure that those systems act together in resisting the horizontal seismic action. The action of floors as diaphragms is especially relevant in cases of complex and non-uniform layouts of the vertical structural systems, or where systems with different horizontal deformability characteristics are used together (e.g. in dual or mixed systems).

The "floor action" is one of the numerous problems which we have encountered while attempting to apply standard code provisions, which are targeted to usual buildings (office, residential, ...), to structures like the one here considered; in some cases we found the provisions simply impossible to be fulfilled. This is the case of horizontal diaphragms or bracing systems, which should be introduced at all levels where horizontal beams develop a load carrying action; this is clearly impossible in a pipe rack of the type here considered, both for the difficulty of defining the relevant levels (longitudinal and transverse beams run at different heights) and for the almost sure interference with the piping layout.

In situations of this type we tried to apply the principle more than the specific rule; in the case of conflicting issues, as for vertical bracing systems, we chose to satisfy what we regarded as the more important aspect; the idea is, in future developments of the research, to validate the design choices here adopted, sometimes violating code provisions, by performing refined non-linear analysis of some prototype structures under dynamic actions due to seismic events of different severity.

Coming back to the case study, we have introduced a horizontal bracing system only at the top of the structure, this being the most efficient position on structural grounds and an almost trouble-free option in terms of compatibility with equipment.

3.2.4 Stiffness 2: composite steel-concrete columns and the versatility concept

In the case study wide-flange laminated columns were encased in a concrete fire protection at the first floor. Concrete was regarded as non-structural given its high probability to be removed or heavily damaged for connecting pipes and pieces of equipment to the steel element. In this study it was proposed to investigate the use of hollow steel sections filled with reinforced concrete on site, with the following advantages:

- concrete stiffness and strength is exploited;
- weight at transportation is reduced;
- concrete pouring is easy;
- equipment connection to the columns is easier.

The proposal must be obviously checked in terms of fire resistance; the internal concrete provides beneficial thermal inertia, but an external protection could be necessary for higher performance. In addition the development of standardized joint connections between tubular columns, laminated beams and braces should be pursued.

The use of steel hollow sections can be seen as a first attempt to introduce the versatility concept; the bare section, and its connections to adjoining elements, can be introduced as the basic structural solution. Its performance can be upgraded in terms of structural and fire resistance just by adding internal concrete and/or external protections, thus minimising the modifications to the overall design.

3.2.5 Seismic design strategy for Ultimate Limit States

The seismic design strategy strongly depends on the behaviour factor (q factor in Eurocode 8), which allows for the reduction of the internal forces computed through a linear analysis, accounting for the beneficial effect of the “ductility of the structural system”. The latter term is to be intended in a broad sense, covering both a stable and reliable hysteretic behaviour at the material/element level and a favourable global structural dynamic response in the inelastic range.

Behaviour factors and regularity

When weight reduction is assumed as the basic design target, the pursuit of the highest possible structural factors seems an obvious choice. This, however, would imply to meet rather strict regularity conditions, in terms of both plan layout and variation of structural properties (mass, stiffness, resistance) with elevation. The latter aspect, i.e. regularity in elevation, conflicts with the necessity of being free to place equipment-carrying elements (i.e. beams) at irregularly spaced vertical positions; for this reasons, a reduction factor of 0.8 has been accepted in applying Eurocode 8 provisions to account for lack of regularity.

Behaviour factors and local ductility

Another fundamental aspect affecting behaviour factors at the local level is the section geometry, which affects phenomena like local buckling. In this respect compact sections or laminated section having small width-to-thickness ratios are rewarded by all seismic codes. In Eurocode 8, high and medium ductility structures, with remarkable difference in the q factors, are defined according to section properties: in the case-study example, beams and columns sections met the conditions for the high ductility. Nevertheless, it was decided to treat the structure as a medium ductility one; this was seen as a compromise solution, accounting for other code provisions that cannot be fulfilled by the design. It must be also noted that when very large behaviour factors are introduced, as it happens for high ductility structures, seismic design is prone to be governed by serviceability conditions, which must be checked in the elastic range and do not benefit from the q value; therefore, increasing the latter does not automatically imply a reduction in element size/weight.

Bracing systems and behaviour factors

An additional aspect that has been addressed in the case study is related to the so called “Chevron” (inverted V) braces, which are rather popular in the design of industrial structures even though in

Eurocode 8 they are penalized by a low value of the behaviour factor, equal to half the one granted to traditional X bracings; such low value is consistent to the design approach implicit, though not declared, in the code. For this reason, an alternative design approach has been followed herein, which justifies the use of the same behaviour coefficient as for X braced systems; this is achieved at the cost of modifying the design of the top beam, to which the diagonal braces are connected, in order to increase its resistance and lateral stability. This can also contribute to the versatility goal, since the modification of few elements leads to a significant upgrade of the seismic performance of the system.

3.2.6 Seismic design strategy for damage limitation

Seismic design of steel structures is often conditioned by the damage limitation state (DLS) for frequent events, i.e. having a return period of the order of the service life, rather than to resistance and ductility under the strong motion, characterized by a much lower probability of occurrence. This is the typical design situation for moment resisting frames (MRFs), which are intrinsically deformable and thus prone to non-structural damage in serviceability conditions, but ensures very favourable design coefficients against ultimate limit state (ULS) seismic actions.

A similar situation occurred, in the case study here performed, when the design of transverse frames against high-level seismic forces was addressed; it was found that the MRF resistance fulfilled the requirements of Eurocode 8 against ULS, while was too deformable to satisfy no damage requirements. A non-conventional design solution was proposed (following [11]), based on the introduction of a bracing system whose contribution was accounted for stiffness, within the context of DLS, but disregarded in ULS checks regarding resistance and ductility. This solution, allowing for the use of slender braces and lighter joints, can be seen again as an application of the versatility concept.

4 | Conclusions

This work presented the results of a wide spectrum research on plant modularisation. The three objectives of the study were to:

- compare concepts expressed in literature and actual practices
- assess these practices in order to identify gaps to fill for an enhanced modularisation applicability;
- analyse some of the identified technical criticalities in order to boost the development of general and on hand design solutions.

In order to fulfil this threefold purpose a survey was conducted among a significant sample of the Italian EPC project delivery chain. The survey's results are disclosed in chapter one that consists of four sections.

Section one presented the literature review, with particular reference to drivers and criticalities generally associated with modularisation. Section two explained the questionnaire structure highlighting methodological aspects, enlisting the companies involved in the survey and specifying the interviewed roles.

Section three showed and analyzed in depth the interviews results. The first of them is a new definition of modularisation consistent with the actual practices of a significant sample of the Italian EPC supply chain. Furthermore an identification and a semi-quantitative prioritisation of modularisation driving factors and constraints was obtained. Schedule, Site conditions and Labour related issues showed to be the most important drivers for modularisation. On the other hand Modules

Engineering, Module transport and the higher Complexity associated to modular projects are considered major constraints to the choice of this construction strategy.

Section four, on the basis of the survey results, identified several improvement areas in modularisation management. The aim is to provide ideas on the way of the definition of a new management framework for modular plants projects, since standard management approaches showed to effectively not address this kind of projects. The study highlighted that the hinges of such a management framework should be prompt decision making tools able to cope with uncertain and scarce information as well as proper organisational structures and supervision tools. Procurement and engineering activities should be customised for modularisation, considering every existing feed-back loop from the early stages of the project, maximising modules' functional completeness and minimising the reduction in components commonality due to the decoupling of procurement activities for different modules. Also new contractual forms customised for modular plant projects was pinpointed as a main need in order to avoid conflicts and maximise the benefits for all the stakeholders involved in the project.

As a second purpose of this report some engineering aspects related to mudule handling and transportation and to their structural analysis and design are discussed. In this light, in chapter two an overview of the problems criteria and solutions is presented in relation to the procedures for module sea transportation and land transportation by means of SPMTs (Self Propeller Modular Trailers): attention is devoted to

» the definition of the sea motion, related to the safety of fastening and grillage procedures, and to the resistance of the modules;

» the choice of the vessel and the verification of its strength and stability;

» the safety and functionality of loadin and loadout operations, including considerations about the effect of the tidal range, the characteristics of the quay and the SPMT operation;

» the configuration of the hydraulic system supporting the wheel boogies of the SPMT;

» the resistance and stability of the SPMT.

Finally, chapter three has been devoted to structural analysis and design of modules; an attempt to draw some general consideration has been made, based on the results of a case study regarding a real life pipe rack and described in detail in the Appendix.

These consideration address two fundamental issues; the first points to the necessity of developing, for each identified class of modules, standardized design criteria and procedures, leading to the definition of what we called “versatile” solutions. In these solutions, a basic structure, suitable for resisting favourable loading conditions (tipically seismic, wind and lifting/transportation), can be upgraded to more demanding situation by adding or modifying a few structural elements.

As a second remark, we can observe that such standardized procedure would strongly benefit from the development of a "code of practice", based on the provisions of an international code (e.g. the Eurocodes) and aiming to extract from the code itself a selection of suitable and standardized design options. This activity could also lead to some proposal for interpreting or modifying code provisions, in order to meet the characteristics of the modularized structural systems; obviously, these proposals should be strongly supported by a RD activity, in order to demonstrate their feasibility and validity. A typical example should be the performance of refined non-linear dynamic analyses for supporting some innovative proposals in the field of seismic design.

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APPENDIX A: Questionnaire

Interview on modularisation management

Interviewee: ....

Position within the company:..

Company: ....

Date:...

Interviewer: ....

Introduction

Questionnaire

I. Definition of modularisation

a. What do you understand by the term modularisation? Can you provide an example on this?

Definition	Example

b. In your opinion, which of the following definitions best expresses the concept of modularisation/ modularity? Can you rank these?

Definition of modularity	Ranking (1-4)
"Modularity is a general systems concept; it is the extent to which a simple or complex industrial product can be broken down and reassembled." [1]	
[...] the definition of modularisation is: decomposition of an industrial product into minor or major parts or blocks(modules) , fabricated and assembled offsite ,including , to the maximum extent, complete or partial systems, moving offsite productive MHRs. [2]	
"Modularity [...] is a bundle of characteristics that define (a) interfaces between elements of the whole, (b) a function-to-component [...] mapping that defines what those elements are, and (c) hierarchies of decomposition of the whole into functions, components, tasks etc." [3]	
"Product modularity is a systems design strategy that can be used to: 1) manage complexity by hierarchically decomposing a whole into parts and by mapping functions to parts in order to minimise interdependencies, to thereby enable the pursuit for 2) economies of scale by standardising such parts and 3) variability through standardised interfaces that allow the use of interchangeable such parts, or 4) other such benefits." [4]	

c. Considering the following areas of interest in respect of modularisation, have you had any specific experience of them in your professional career? Can you provide examples for the cases presented?

Num.	Areas of application	Importance
1	Product	
2	Plant	
3	Yard	
4	Intangible product: software	
5	Knowledge & Capabilities	
6	Service	
7	Organization	
8	Function	
9	Documentation	

a. In your professional opinion, who are the main decision makers about the need of modularisation? For what reasons?

Num.	Internal Actors	Main reasons
1		
2		
3		
4		
5		
Num.	**External Stakeholders**	**Main reasons**
1		
2		
3		
4		
5		

b. Considering your professional experience, which "actors" usually advocate against modularisation? What are their arguments and what are their motives?

Num.	Internal Actors	Main arguments	Main motives
1			
2			
3			
4			
5			
Num.	**Internal Actors**	**Main arguments**	**Main motives**
1			
2			
3			
4			
5			

II. Driving factors and objectives

a. Can you list the main factors driving the modularisation? Please assign a score between 0 and 100 according with the estimated importance of each driver.

Num.	Drivers	Importance
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

b. Can you make an example for each of the mentioned "Drivers"?

Num.	Examples of Drivers
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

c. In your opinion, which of the following purposes best express the objectives associated to modularisation for each stakeholder? Please assign a score between 0 and 100 according with the estimated importance of each purpose.

Num.	Purposes of modularisations	IMPACT			
		EPC	Service Provider	Utility	Manu-facturer
1	Balance standardization with customization				
2	Reducing project cost				
3	Reducing project delivering time				
4	Reducing complexity				
5	Reducing risk				
6	Reducing design and/or manufacturing efforts				
7	Enhancing project manageability				
8	Enhancing market competiveness (e.g. better services)				
9	Enhancing innovation				
10	Increasing safety				
11	Increasing construction efficiency				
12	Reducing and shortening of MPW peak (on site)				
13	Reducing imported MPW				
14	Mitigating the lack of lay-down areas constraints				
15	Mitigating social impacts at site due to construction				
16	Increasing sustainability of the site works				

III. Modularisation constraints

d. Can you list what you think are the most critical issues (e.g. barriers, constraints) associated with modularisation? Please assign a score between 0 and 100 according with the estimated importance of each issue.

Num.	Issue	Importance
1		
2		
3		
4		
5		
6		
7		
8		
9		

e. Please provide examples for the mentioned barriers and constraints?

Num.	Examples of barriers and constraints
1	
2	
3	
4	
5	
6	
7	

f. According with your experience, in which way do you remove or limit the effect of the barriers and constraints to the use of modularisation?

Num.	Methods to remove or limit barriers and constraints
1	
2	
3	
4	
5	
6	
7	
8	
9	

Note

APPENDIX B: Case study

B.1 Analysis of the structural response to wind loads

In serviceability conditions, the modular structure considered in this case-study is subject to the external loads summarized in the following table.

CATEGORY	LOADS
Permanent, structural	Self weight, Dead load
Permanent, non-structural	Fire proofing, Piping weight
Accidental	Anchor forces, PSV, Operating loads, Wind & snow, Seismic load

Table B.1: loading conditions

It is worth noting that the considered classification is not intended for the case of transient situations. For instance, the transportation phase may involve severe loading conditions, which deserve a thorough treatment and is the subject of ongoing research.

Since the aim is to achieve weight saving via load reduction, it is reasonable to disregard permanent actions (which are normally established by the operative requirements) and to consider a detailed analysis of accidental loads. More specifically, focus will be on wind and seismic actions, which are the heaviest loads in many practical situations.

B.1.1 Wind action: the structural factor

By considering the Eurocode 1, part 1.4, on finds that the wind actions can be represented by the following static equivalent forces:

$$F_W = c_s c_D c_f q_p (z_s) A_{ref}$$

q_p is the peak velocity pressure, which in turn depends on the wind velocity and the exposure coefficient at height z_s. A_{ref} is the reference area, which is properly modified by the force coefficient c_f: the latter is usually obtained by the code or from literature data.

This section contains the detailed study of a sensible coefficient, namely the structural factor $c_s c_d$, which is precisely defined in the Eurocode 1 Part 1.4:

6.1 General

(1) The structural factor $c_s c_d$ should take into account the effect on wind actions from the non-simultaneous occurrence of peak wind pressures on the surface (c_s) together with the effect of the vibrations of the structure due to turbulence (c_d).

The aforementioned Standard provides a detailed procedure for the numerical evaluation of the structural factor. The detailed description is reported in the Annex B of Eurocode 1 Part 1.4 and it is not reported in this document for the sake of brevity. Some general information are usefully reminded: 1) the non-simultaneity coefficient c_s is basically dependent on the turbulence features and on the structural dimensions; 2) the latter are referred to parts of the structure which simultaneously and independently supports the wind action; 3) the dynamic coefficient cd depends also on the dynamic behaviour of the structure, which affects some specific aerodynamic coefficients; 4) the dynamic features are assumed to be summarized by the properties of the fundamental vibrating mode (frequency, shape and damping factor).

It is worth noting that such a procedure has been developed for some specific cases (i.e. slender civil buildings, horizontal structures, pointlike structures) which do not encompass the considered structure. Nevertheless, the procedure has been applied and a specific validation has been provided by dynamic analyses.

B.1.2 Structural factor for the original layout

As a first step, the original layout of the pipe-rack has been considered. The modal analysis yielded a set of closely spaced modes, which are referred to single transversal frames. The situation is depicted in Figure B.1, which contains the plan view of the first three vibrating modes: it is clear that, in the absence of specific horizontal bracing, each single frame vibrates independently with respect to the adjacent frames.

Taking this structural behavior into account, the non-simultaneous action of wind should not be considered on the whole structural assembly but, more realistically, on each single bay connected to the vertical frame. The structural factor is thus computed by considering the frequency of the first natural mode and a structural width equal to the frame spacing (namely, b = 6 m). The computation of the structural factor is summarized in the following tables, where the naming convention is in agreement with Eurocode 1.

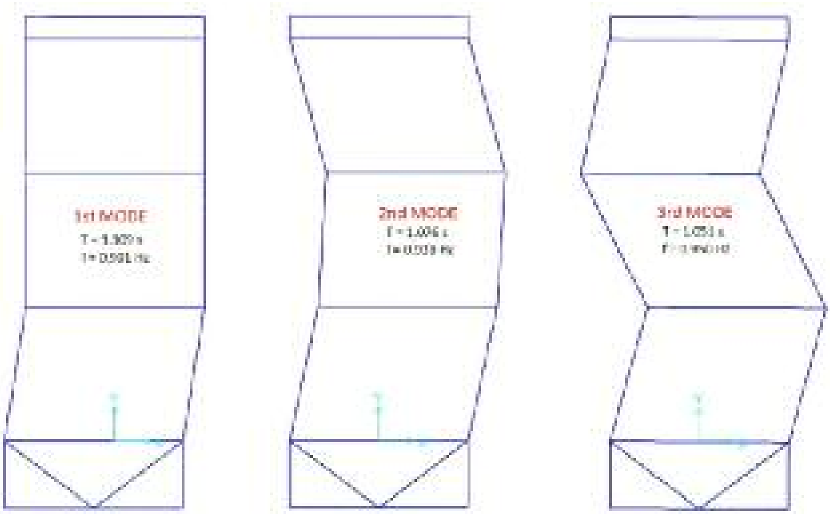

Figure B.1 - Plan view of the first three vibration modes for the original layout of the pipe rack, in the absence of horizontal bracing; the frequency and the period of vibration are indicated for each mode.

The computation yields a structural factor which is considerably larger than one: the nominal wind action on the pipe rack should be increased by about 28% in view of the unsatisfactory dynamic behavior of the structure. A plain provision in order to reduce the wind action is represented by the introduction of some structural connection between the transverse frames.

B.1.3 Modified layout: horizontal bracing system

In the previous section, the structure has been considered to be composed by four independent transverse frames, in the absence of specific connecting elements. This situation is clearly harmful for the structural factor; moreover, further drawbacks are represented by the structural response to random and non-simultaneous loads (connected for instance to the Pressure Safety Valves) and by the interaction with the technological equipment. The former issue will be treated at the end of this section. Now, it is worth spending some words on the fact that the structure is designed with the purpose of containing several pipe lines, which may run in the longitudinal direction. In principle, such elements could provide a certain constraint for the relative movement of adjacent frames. As a matter of fact, the common tendency in the design procedure is to consider the pipes as non-structural elements, with the purpose of avoiding additional stress which may endanger the plant operation. In this sense, the presence of horizontal bracing could represent a beneficial provision because it removes the loads acting on the pipes due to relative displacement of the transverse frames.

Wind load analysis		
Fundamental value of wind velocity [m/sec]	$v_{b,0}$ =	26.2
Directional factor	c_{dir} =	1
Season factor	c_{season} =	1
Basic wind velocity [m/sec]	v_b =	26.2
Height of the building [m]	h =	17
Terrain category		II
Roughness length [m]	z_0 =	0.05
Minimum height [m]	z_{min} =	2
Terrain factor	k_r =	0.19
Roughness factor	$c_r(h_e)$ =	1.01
Orography factor	$c_0(h_e)$ =	1
Mean wind velocity at height he [m/sec]	$v_m(h_e)$ =	26.47
Turbulence factor	k_l =	1
Standard deviation of the turbulent component of wind velocity	σ_v =	4.927
Turbulence intensity	$I_v(h_e)$ =	0.188
Exposure factor ($1+7I_v$)	$c_e(h_e)$ =	2.316
Air density [kg/m³]	ϱ =	1.25
Mean velocity pressure at height he [N/m²]	$q_b(h_e)$ =	438
Peak velocity pressure at height h_e [N/m²]	$q_p(h_e)$ =	1015

Table B.2 - **Wind load analysis table**

Structural factor		
Reference height [m]	z_s =	10.2
Roughness factor	$c_r(z_s)$ =	1.01
Orography factor	$c_0(z_s)$ =	1
Mean wind velocity at height z_s [m/sec]	$v_m(z_s)$ =	26.474
Turbolence intensity at height z_s	$I_v(z_s)$ =	0.188
Basic velocity pressure at height z_s	$q_b(z_s)$ =	438.03
Peak velocity pressure at height z_s [N/m²]	$q_p(z_s)$ =	1014.6
Building width [m]	b =	6
Reference scale lenght [m]	L_t =	300
Reference height [m]	z_t =	200
Coefficient [m]	α =	0.52
Turbulence lenght scale [m]	$L(z_s)$ =	63.79
Background factor	B^2 =	0.679
Duration of the design event [s]	T =	600
Natural frequency of the building [Hz]	n_{1x} =	0.901
Non dimensional frequency	$f_L(z_s,n_{1x})$ =	2.171
	η_h =	2.661
	η_b =	0.939
Loss of correlation factor (vertical)	R_h =	0.30549
Loss of correlation factor (horizontal)	R_b =	0.5845
Non dimensional power spectral density function	S_L =	0.07854
Structural damping (logarithmic decrement)	δ_s =	0.05
Aerodynamic damping (logarithmic decrement)	δ_a =	0.00033
Damping due to special devices	δ_d =	0
Total damping (logarithmic decrement)	δ =	0.05033
Resonance response factor	R^2 =	1.37498
Up-crossing frequency	ν =	0.73723
Peak factor	k_p =	3.66247
Structural factor	c_sc_d =	1.2839
Size factor	c_s =	0.8999
Dynamic factor	c_d =	1.4267

Table B.3 - **Structural factors table**

After several preliminary studies, it has been obtained that the desired target can be reached by considering a single bracing system, on the top level of the pipe rack. This layout is endowed with several positive features: 1) structural efficiency; 2) minimum interference with piping system; 3) full compatibility with the common pipe rack arrangement (staggered horizontal beams in the intermediate floor, not on the top level). The modified layout is depicted in Figure B.2, which shows the cross-bracing system constituted by simple T-shaped steel elements.

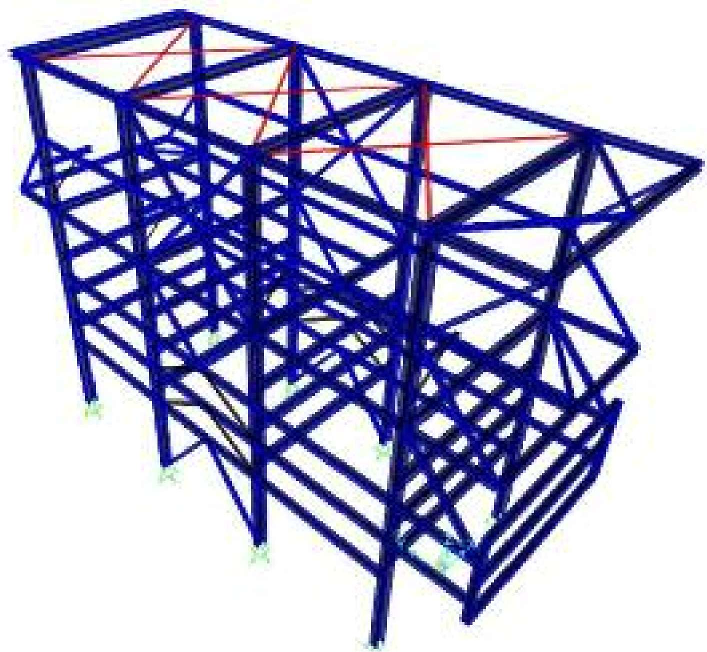

Figure B.2 - Modified layout, with horizontal cross-bracing on the top level.

With this simple provision, which entails a negligible addition of material, the dynamic behavior is substantially changed: all the transverse frames are now involved in the first vibration mode, characterized by a natural frequency which is slightly higher with respect to the original case. Figure B.3 shows the first modal shape (transverse view and three-dimensional view).

In view of the cooperation of the four transverse frames, the structural factor can be tentatively computed by changing the reference width, which should be chosen as the overall width of the pipe-rack. In this way, both the size factor and the dynamic factor are reduced, finally obtaining a structural factor equal to 1.10 (-14% w.r.t. the original value).

As anticipated, the presence of a horizontal bracing system is also advantageous for the loading

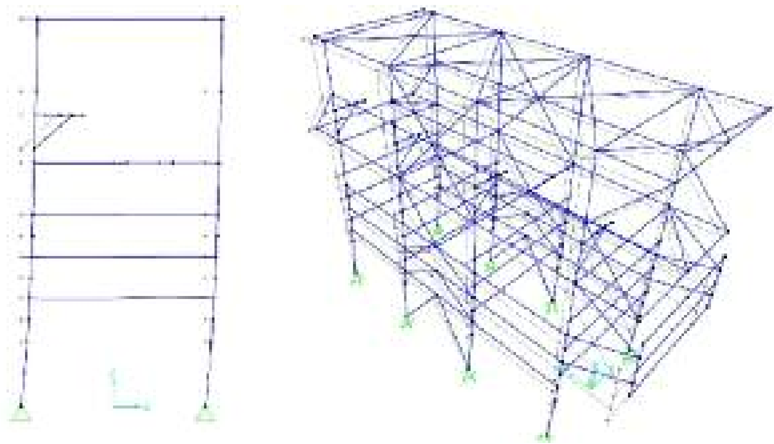

Figure B.3 - Shape of the first vibrating mode, in the presence of the horizontal cross-bracing system; natural frequency of the considered mode: 0.93Hz.

condition represented by the release of Pressure Safety Valve (PSV). PSVs, which are usually concentrated on the top floor of the pipe rack, automatically release the fluid from the piping system, when the pressure (or temperature) exceeds preset limits. The sudden release of fluid involves a dynamic effect, which, for design purposes, can be represented by concentrated loads in the transverse direction. The effect is essentially impulsive, as its duration is by far shorter than the structural fundamental period. It should be noted that the loading condition is mainly related to the first transverse mode; by neglecting the effects of damping, which are of minor importance for the evaluation of the response peak, the single-mode oscillations due to an impulsive effect are essentially harmonic. The combination of the effects of various PSV_S is thus coincident with that among harmonic responses sharing the fundamental frequency. If one considers the phases, the main outcome is that the precise timing of the PSV activation is not predictable; however, for technological reasons, the simultaneous activation of the valves is highly unlikely. Assuming that the above phases are uncorrelated, a generic mechanical effect R on the structure can be computed by combining the effects of each single PSV Ri by means of the SRSS formula (Square Root of the Sum of Squares):

$$R = \sqrt{\sum_i R_i^2}$$

It is quite easy to realize that, in the case of independent frames, there is no difference with respect to the standard computation for simultaneous application of the PSV load. In fact, the PSV action is just balanced by a single frame, with no cooperation of the adjacent ones. Conversely, the presence of the horizontal brace is beneficial both for the participation of the whole structure and for the further reduction due to non-simultaneity of the external load. A numerical comparison is provided by considering the bending moment in the most loaded frame, for the PSV action. In the case of independent frames, the maximum bending moment is 8.31 kNm; conversely, by applying the SRSS superposition in the case of horizontal brace, one obtains 3.39 kNm. A 60% reduction of bending moment in the transverse frame is hence obtained.

B.1.4 Further modification: stiffened columns

As it has been stated in the introductory Section, the structural stiffness can be also increased by introducing a modification to the column design, which is usually based on rolled section steel profiles protected by non-structural concrete as a fire-proofing provision. As a promising alternative the adoption of hollow sections filled by poured concrete has been here considered. This modification entails an increase of stiffness in view of the possible collabouration between steel and concrete elements. Note that the concrete covering of standard I-shaped beams is exposed to the risk of in-situ demolition and reconstruction for plant requirement which may intervene during the structure lifetime. For this reasons, it is common practice to neglect the presence of concrete from the structural point of view. Conversely, in the case of concrete inside hollow sections, such a risk is completely eliminated and, by introducing some suitable steel- concrete connection, a composite cross-section can be considered in the structural analysis. The lateral stiffness is thus increased, with the consequence of more favorable dynamic response to the wind action. Clearly, the computation of cross-section inertia should comply with the standard restrictions. For instance, in order to take into account the non-perfect adherence of the heterogeneous materials and the concrete cracking under tensile load, a corrective coefficient (lower than unity) should be introduced when computing the concrete contribution.

The analysis has been carried out by considering both the horizontal bracing system and the modified columns (see Figure B.4). The latter are filled with concrete until the level +4.68 m, which correspond to the first floor level.

The fundamental vibrating mode of the modified structure is quite similar to the previous case, and, for this reason, no graphical representation is reported herein. Conversely, there is a significant variation of the fundamental frequency which now attains the value 1.28 Hz. The structural factor has been computed in this situation and a value close to unity is obtained, in view of a substantial reduction of the dynamic factor. It is finally possible to conclude that an increase of the structural stiffness, given by a horizontal bracing system and a modification of the columns,finally yields the desired compensation between dynamic amplification and non-simultaneous effects.

4.1.5 Validation via dynamic analysis

The structural factor has been computed on the basis of analytical expressions provided by the Eu-

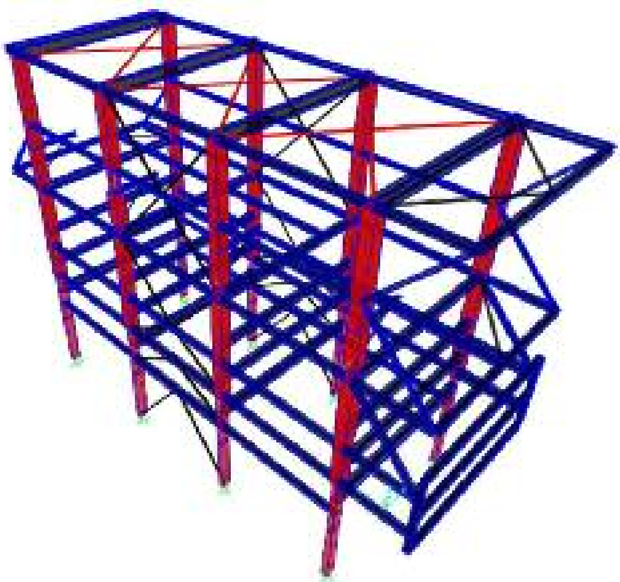

Figure B.4 - Modified layout, with horizontal cross-bracing on the top level and hollow columns filled with concrete until the first floor level (i.e. +4.68 m above the foundation level).

rocode 1, Part 1.4. The application of such formulas is restricted to some simple structural cases, representing, on aerodynamic grounds, point-like or slender bodies, excluding extended structures as the pipe rack considered herein. It must be said that the aerodynamic behaviour of a typical pipe rack should deserve detailed experimental investigation in order to characterize the pressure distribution on the structural and equipment components. Here, the application of the simplified procedure of Eurocode 1 has been validated in terms of structural behaviour by performing a critical comparison with respect to a complete dynamic analyses. In particular, a step-by-step dynamic analyses was performed, characterized by the application of forces whose space-time distribution is consistent to the stochastic model of turbulence which is the basis of the definition of the dynamic coefficient.

The analysis is based on the same hypotheses as adopted in the simplified procedure, i. e. the definition of the action of the wind as a superposition of two effects: a static force due to the mean velocity and a dynamic one due to the fluctuations of the velocity and aerodynamic damping. The latter component of the dynamic force is neglected, while the former (due to wind fluctuation) is represented as a set of dynamic concentrated forces that are directly applied to the model, along with the static components. The following assumptions apply :

- only the effects of drag forces is considered (neglecting the lift)

- the transverse component of turbulence is neglected The static component of the wind force is defined as:

$$F_{j,sta} = \frac{1}{2} \rho A_j C_{F,j} W^2(z_j)$$

where ρ is the air density, A_j is the surface area exposed at node j, $C_{F,j}$ is the coefficient of aerodynamic force, $W(z_j)$ is the value of the average speed at level z_j.

The dynamic component of wind force is defined as:

$$F_{j,dyn} = \rho A_j C_{F,j} W(z_j)\, w(z_j,t)$$

where $w(z_j,t)$ is the component in the direction of the wind fluctuation due to turbulence at level z_j. For the determination of this component, it is necessary to generate the time history of the fluctuating velocity, through a stochastic model of wind fluctuations. The model takes into account, via the space coherency function, the correlation of the turbulent components in the different application points. Each generated time history of the fluctuation corresponds to a dynamic component of the wind force, that is superimposed to the static component of the point in question .

Among the outputs of the analysis, for the purpose of comparison, the shear force at the base of each column is considered. The analysis has been referred to the modified layout, in the presence of horizontal bracing systems and stiffened columns. The peak force has been extracted from the time history of shear forces, obtained by means of the dynamic analysis and summed to the static component; the comparison has been carried out with respect to the analogous force, that is statically computed by applying the wind action modified by the structural factor. In this way, the result of the more refined analysis is compared to the static-equivalent analysis and the procedure for obtaining the structural factor can be validated. The outcomes of the comparison are reported in the next table.

Good agreement between the two analyses is obtained. A maximum discrepancy of 32% is obtained on column 6, but the most important thing is that the static-equivalent analysis is on the safe side. The maximum force, which is normally used in order to design all the columns, is caught with excellent precision (3% error) by the static-equivalent analysis.

From the above results, it is possible to conclude that the procedure reported in Eurocode 1 for the structural factor can be successfully applied to this kind of structure, provided that a validation is performed in terms of aerodynamic behavior.

Column n.	Shear force (kN)	
	Dynamic analysis	Static-equivalent analysis
1	33.06	31.15
2	34.15	35.64
3	36.93	35.65
4	36.93	32.50
5	26.97	31.15
6	26.98	35.64
7	27.54	35.65
8	27.50	32.51

Table B.4 - results of wind analysis

B.2 Seismic analyses

The achievement of an earthquake-resistant structure involves the examination of several specific issues. Most of them are related to the capability of the structural system to dissipate the kinetic energy due to ground shaking, thus avoiding the catastrophic collapse at the price of severe plasticization in specific elements. Moreover, a proper seismic design should also entail an acceptable behavior in exercise conditions, for the cases of earthquake endowed with lower severity and shorter return time: in general, the serviceability conditions for steel structures are related to the limitation of horizontal relative displacements between adjacent stories.

The purpose of this Section is to provide some specific hints for the design of modular systems in seismic areas. Two possible scenarios are considered: moderate values of PGA (peak ground acceleration), around 0.2 g; severe earthquake conditions, with PGA around 0.4 g. In this way, it will be possible to highlight different structural concerns, both for the ultimate limit state and for the exercise conditions. As a preliminary step, the problem of the correct evaluation of the behavior factor is thoroughly treated. Then, the main results for the seismic analyses of the case- study (the same pipe-rack as for the previous Sections) are reported in order to introduce the proposed structural modifications and their usefulness.

B.2.1 Proper evaluation of the behavior factor

The first step in a seismic analysis consists in the definition of the behavior factor (called q in the Eurocode 8). This factor is involved in the definition of the design actions in case a linear dynamic analysis is carried out as an approximation of the truly nonlinear behavior of the structure (of course, if the Ultimate Limit States are considered); in other words, the behavior factor allows one to operate in an easy framework by performing the analysis in the elastic field and then by reducing the results, in terms of internal actions, in order to take account of the dissipation due to inelastic phenomena.

According to Eurocode 8, 3.2.2.5 "the behavior factor *q* is an approximation of the ratio of the seismic forces that the structure would experience if its response was completely elastic with 5% viscous damping, to the seismic forces that may be used in the design, with a conventional elastic analysis model, still ensuring a satisfactory response of the structure". In particular, the behavior factor defines the design spectrum starting from the elastic response spectrum; with the exception of the first linear branch, the design spectrum is obtained from the elastic one through division by *q*:

$$F_{S,d} = \frac{MS_a(T,\xi)}{q}$$

The determination of the behavior factor is influenced by the properties of the structure (symmetry and regularity) and by the ductility at local and global level. Special attention should be paid to the study of the regularity of the structure under consideration. Eurocode 8, 4.2.3.1, reads:

(1)P For the purpose of seismic design; building structures are categorised into being regular or non-regular.

(2) This distinction has implications for the following aspects of the seismic design:

- *the structural model, which can be either a simplified planar model or a spatial model;*
- *the method of analysis, which can be either a simplified response spectrum analysis (lateral force procedure) or a modal one;*
- *the value of the behaviour factor q, which shall be decreased for buildings non-regular in elevation.*

Table B.5 indicates the effects of structural regularity on the seismic analysis and design; it is worth noting that, if the requirement is not met, the behavior coefficient must be penalized. The requirements for regularity in elevation are summarized in section 4.2.3.3 of Eurocode 8:

Regularity		Allowed Simplification		Behaviour factor
Plan	Elevation	Model	Linear-elastic Analysis	(for linear analysis)
Yes	Yes	Planar	Lateral force [a]	Reference value
Yes	No	Planar	Modal	Decreased value
No	Yes	Spatial [b]	Lateral force [a]	Reference value
No	No	Spatial	Modal	Decreased value

a If the condition of 4.3.3.2.1(2) a) is also met.

b Under the specific conditions given in 4.3.3.1(8) a separate planar model may be used in each horizontal direction, in accordance with 4.3.3.1(8)

Table B.5 - Consequences of structural regularity on seismic analysis and design

Criteria for regularity in elevation

(...)

(2) All lateral load resisting systems, such as cores, structural walls, or frames, shall run without interruption from their foundations to the top of the building or, if setbacks at different heights are present, to the top of the relevant zone of building.

(3) Both the lateral stiffness and the mass of the individual storeys shall remain constant or reduce gradually, without abrupt changes, from the base to the top of a particular building.

(4) In framed buildings the ratio of the actual storey resistance to the resistance required by the analysis should not vary disproportionately between adjacent storeys.

(...)

The case-study does not meet the regularity requirements: hence the behavior factor should be suitably modified. To this purpose, it is necessary to study the specific features of the structure, in terms of building material and geometric configuration

Chapter 6 of Eurocode 8 is entirely devoted to steel buildings. In section 6.3.1 the possible structural types are briefly described:

a) Moment resisting frames, are those in·which the horizontal forces are mainly resisted by members acting in an essentially flexural manner.

b) Frames with concentric bracings, are those in which the horizontal forces are mainly resisted by members subjected to axial forces.

c) Frames with eccentric bracings, are those in which the horizontal forces are mainly resisted by axially loaded members, but where the eccentricity of the layout is such that energy can be dissipated in seismic links by means of either cyclic bending or cyclic shear.

d) Inverted pendulum structures, are defined in 5.1.2, and are structures in which dissipative zones are located at the bases of columns.

e) Structures with concrete cores or concrete walls, are those in which horizontal forces are mainly resisted by these cores or walls.

f) Moment resisting frames combined with concentric bracings.

g) Moment resisting franles combined with infills.

The frame studied herein can be attributed to the category a (moment resisting frames) with respect to the transverse direction and b (frames with concentric bracing elements) for the longitudinal direction where there are V-brace concentric elements; Figure B.5 shows the representation of the categories a) and b), as reported in the Eurocode.

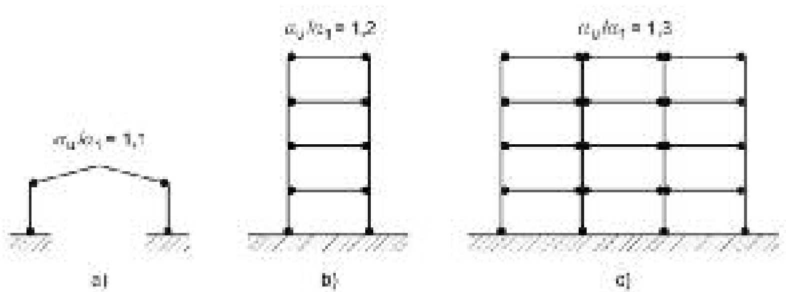

Figure B.5 - Moment resisting frames (dissipative zone in beam and at bottom of column). Default value for α_u/α_1 (see 6.3.2(3) and Table 6.2)

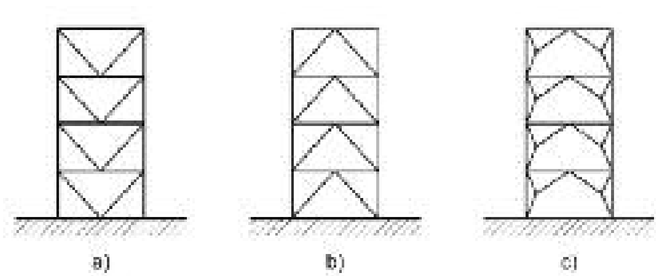

Figure B.6 - Schematic drawing of moment resisting frames (which are representative of the transverse frames in the present case) and frames with concentric bracings (V-bracings are present in the longitudinal frames).

Section 6.3.2 of the Eurocode lists the requirements for the selection of the behavior factor:

"The behaviour factor q, introduced in 3.2.2.5, accounts for the energy dissipation capacity of the structure. For regular structural systems, the behaviour factor q should be taken with upper limits to the reference values which are given in Table 6.2 (Table B.6, editor's note), provided that the rules in 6.5 to 6.11 are met.

If the building is non-regular in elevation (see 4.2.3.3) the upper limit values of q listed in Table 6.2 (Table B.6, editor's note) should be reduced by 20 % (see 4.2.3.1(7) and Table 4. I)."

STRUCTURAL TYPE	Ducility Class	
	DCM	DCH
a) Moment resisting frames	4	$5\,\alpha_u / \alpha_1$
b) Frame with concentric bracings		
Diagonal bracings	4	4
V-bracings	2	2,5
c) Frames with eccentric bracings	4	$5\,\alpha_u / \alpha_1$
d) Inverted pendulum	2	$2\,\alpha_u / \alpha_1$
e) Structures with concrete cores or concrete walls	See section 5	
f) Moment resisting frame with concentric bracings	4	$4\,\alpha_u / \alpha_1$
g) Moment resisting frames with infills		
Unconnected concrete or masonry infills, in contact with the frame	2	2
Connected reinforced concrete infills	See section 7	
Infills isolatd from moment frame (see moment frames)	4	$5\,\alpha_u / \alpha_1$

Table B.6 - **Upper limit of reference values of behaviour factors for systems regular in elevation**

By considering a medium ductility class (DCM), the value of *q* is equal to 4 and 2 in the transverse and in the longitudinal direction, respectively (it is possible to assign different values for the two different directions), in case the regularity conditions in elevation are fulfilled. Since, however, this requirement is generally not met in a satisfactory manner for the case of modular pipe-racks, it is necessary to introduce a 20% reduction. The final values of the behavior coefficients scale down to 3.2 for the longitudinal direction and 1.6 for the longitudinal frames.

The coefficient in the longitudinal direction deserves specific considerations: the inhomogeneous values of the behavior factor in the two directions may finally yield a non-optimal seismic design. It is thus important to understand if it is possible to raise the value in the longitudinal frames, without changing the bracing scheme which is characterised by structural simplicity and full compatibility with the service requirements. It must be noticed that the standard imposes a low behavior factor in the case of V-brace (chevron), since it presupposes a static scheme like the one shown in Figure B.7.

Under this hypothesis, the tensile force in one diagonal is limited by the carrying capacity under axial compression of the other diagonal, which may suffer by elastic buckling. It is possible to envisage a different static scheme, shown in Figure B.8, where the flexural response of the beam is involved so that the tensioned brace can reach the plastic strength $(N_{pl,Rd})$, even if the other diagonal has already exceeded the bearing capacity connected to buckling $(N_{b,Rd} \leq N_{pl,Rd})$.

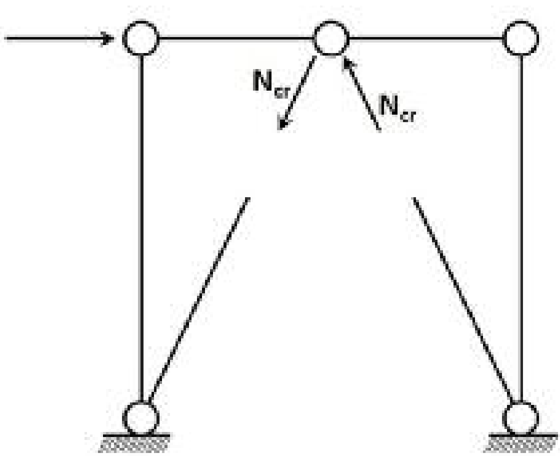

Figure B.7 - Static scheme for the standard interpretation of V-bracing system

In this case, the structural behavior is similar to eccentric bracing, which entails the plastic response of the beam and which is characterized by q = 4 (to be reduce until 3.2 for the non- regularity in elevation). Of course, the increased behavior coefficient is realistic only if the beams are capable of withstanding the unbalanced vertical force at the tip of the V-brace. The vertical action on the beam is given by the difference between Npl, Rd and Nb, Rd, projected in the vertical direction (see Figure B.9)

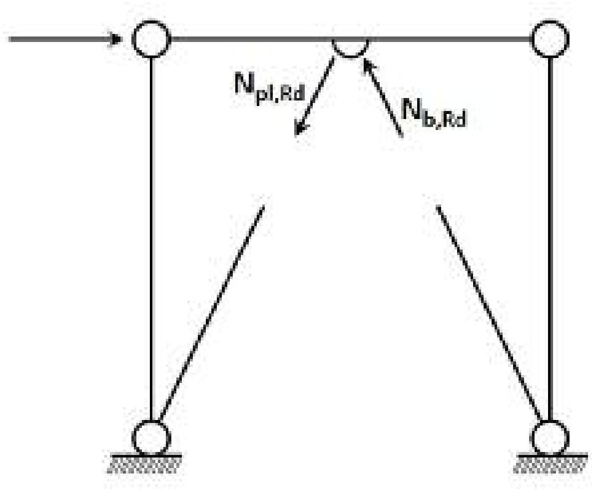

Figure B.8 - Alternative interpretation of the static scheme for the V-bracing system

It is possible to predict a moderate increase of the beam dimension, as a consequence of the flexural involvement in the seismic response. Nevertheless, the parametric studies have shown that the achievement of a uniform behavior coefficient in the two directions is by far more important, in order to obtain the optimal seismic design.

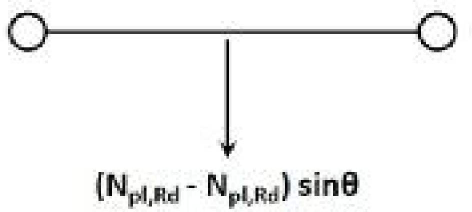

Figure B.9 - Computation of the unbalanced vertical force which entails an additional bending moment on the beams

4.2.2 Operational details of seismic analyses

As already mentioned, the seismic analyses have been carried out for two different earthquake intensities, in order to enlighten the critical issues which are connected to the two scenarios for both the Ultimate Limit States and the Service Limit States.

The scenario of moderate earthquake is represented by a PGA of 0.2 g. The design spectrum for the horizontal actions (which are the most important in the specific case) is defined in the Eurocode 8:

$$0 \le T \le T_B:\ S_d(T) = a_g S \left[\frac{2}{3} + \frac{T}{T_B}\left(\frac{2.5}{q} - \frac{2}{3}\right)\right]$$

$$T_B \le T \le T_C:\ S_d(T) = a_g S \left[\frac{2.5}{q}\right]$$

$$T_C \le T \le T_D:\ S_d(T) = a_g S \frac{2.5}{q}\left(\frac{T_C}{T}\right) \ge \beta\, a_g$$

$$T_D \le T:\ S_d(T) = a_g S \frac{2.5}{q}\left(\frac{T_C T_D}{T^2}\right) \ge \beta\, a_g$$

In the previous formulas: $S_d(T)$ is the design spectrum; T is the vibration period; a_g is the chosen PGA; T_B is the lower bound and TC is the upper bound for the constant branch of the acceleration spectrum; T_D is the starting point of the branch at constant displacement; S is the soil coefficient; q is the behavior factor; defines the lower bound for the design spectrum (recommended value β = 0.2). The values T_B, T_C, T_D, S depend on the soil type and are indicated by the national regulations. In the specific case, the following values have been adopted: S = 1.2; T_B = 0.15 s; T_C = 0.5 s; T_D =2.0 s.

The design spectrum has been introduced in the computer code, as graphically explained in Figure B.10. In the case of severe earthquake conditions, the only modification is referred to the PGA value, which is changed into 0.4 g. The final design spectrum is simply multiplied times a factor 2 with respect to the previous case.

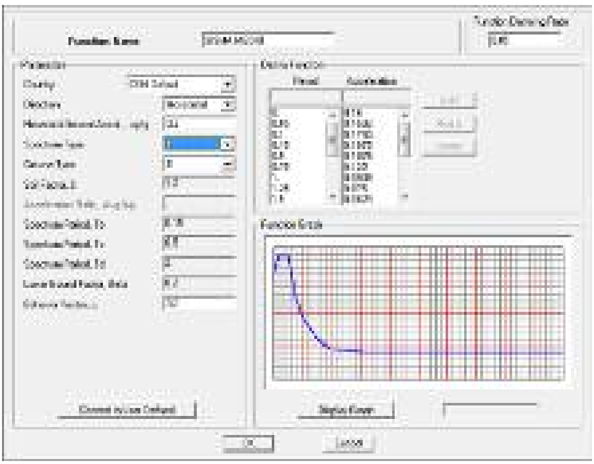

Figure B.10 - Screenshot of the data input for the definition of the design spectrum in the case of moderate seismic intensity

In order to satisfy the basic requirements for the seismic assessment, it is necessary to check the following limit states: ULS and DLS. The load combination is obtained by considering the seismic actions associated to the dead loads $G_{k,j}$ and a portion of the live loads $Q_{k,i}$

$$E_k + \sum G_{k,j} + \sum \Psi_{E,i} * Q_{k,i}$$

The combination factor $\Psi_{E,i}$ accounts for the probability of simultaneity for the maximum credible earthquake and the live loads. In the present case, by considering the recommendations of Eurocode 8 and Eurocode 0 [10], a suitable value is $\Psi_{E,i}$ = 0.3. Moreover, the seismic actions in the two horizontal directions must be combined as follows (vertical excitation can be neglected in this case):

$$E_{Edx}"+"0{,}3E_{Edy}$$

$$E_{Edy}"+"0{,}3E_{Edx}$$

The structural analysis has been carried out by means of a modal superposition technique (in the hypothesis of conventional linear dynamic behavior). This analysis consists of the following steps: (i) determination of the vibration modes of the building (modal analysis); (ii) calculation of the effects of the seismic action represented by the design response spectrum for each of the vibration modes; (iii) combination of these effects. Attention should be paid to the participating mass and either of the following conditions should be satisfied: all modes with participating mass greater than 5% are included in the analysis; a number of modes is considered such that the total participating mass is greater than 90%. For the combination of the effects of the individual modes, a complete quadratic combination is adopted:

$$E_k = \sqrt{\sum \sum \rho_{ij} E_i E_j}$$

E_j is the effect of mode number j and ϱij the coefficient of correlation between mode i and mode j, which can be computed with the following formula:

$$\rho_{ij} = \frac{8\xi^2 \beta_{ij}^{3/2}}{(1+\beta_{ij})\left[(1-\beta_{ij})^2 + 4\xi^2\beta_{ij}\right]}$$

ξ is the viscous damping coefficient and β_{ij} is the ratio between the period of mode *j* and mode *i*.

The combined actions are used for safety assessment. ULS are “associated with collapse or with other forms of structural failure which might endanger the safety of people”, according to Eurocode 8. The safety assessment is carried out by checking the structural strength (with respect to various failure modes, e.g. sectional resistance, overall and local buckling, etc.) and by verifying the fulfilment of some geometric constraints which are connected to the proper development of dissipative zones. It is useful to remind concisely the critical issues for the problem at hand.

Transverse frames (moment resisting frames)

- Beams. Sectional strength for bending, with possible influence of the shear force; buckling for compressive force and for flexural-torsional interaction; limitation of the axial load in the zones where plastic hinges may occur.

- Columns. Sectional strength for axial force, shear force and bending moment, with the suitable overstrength factor in order to achieve a “strong column-weak beam” layout; lateral and lateral-torsional buckling.

Longitudinal frames (concentric bracings)

- Diagonal members. Non-dimensional slenderness less than or equal to 2.0; sectional strength for axial force; limitation of the difference between the maximum and the minimum overstrength

- Beams and columns. Sectional strength for axial force, shear force and bending moment, with the suitable overstrength factor in order to achieve dissipation in the diagonal members only; lateral and lateral-torsional buckling.

DLS are studied “by satisfying the deformation limits or other relevant limits” defined in Eurocode 8. For the specific case, only the interstorey drift should be considered under a seismic action having a larger probability of occurrence than the design seismic action corresponding to the ULS. It is worth noting that the displacements due to seismic actions are obtained by applying the aforementioned design spectrum and by multiplying the computed displacements times the “displacement behavior coefficient”, which in general is assumed to be the same as the standard behaviour factor. In the specific case, it is advisable to consider the presence of brittle non-structural elements, so that the following inequality must be satisfied:

$$d_r \nu \leq 0,005h$$

where is the design interstorey drift and is the storey height. The coefficient is introduced in order to take into account the lower return period of the seismic action; in the present case, it has been assumed .

4.2.3 Safety assessments for the original layout

The results of safety assessments for ULS are presented first. Both seismic intensities lead to the violation (with different levels) of the design requirements which are summarized in the next list.

1) Column strength in the transverse frame: some columns at the top storey do not fulfill the strength requirement in terms of combination of axial forces and bending moment (Figure B.11).

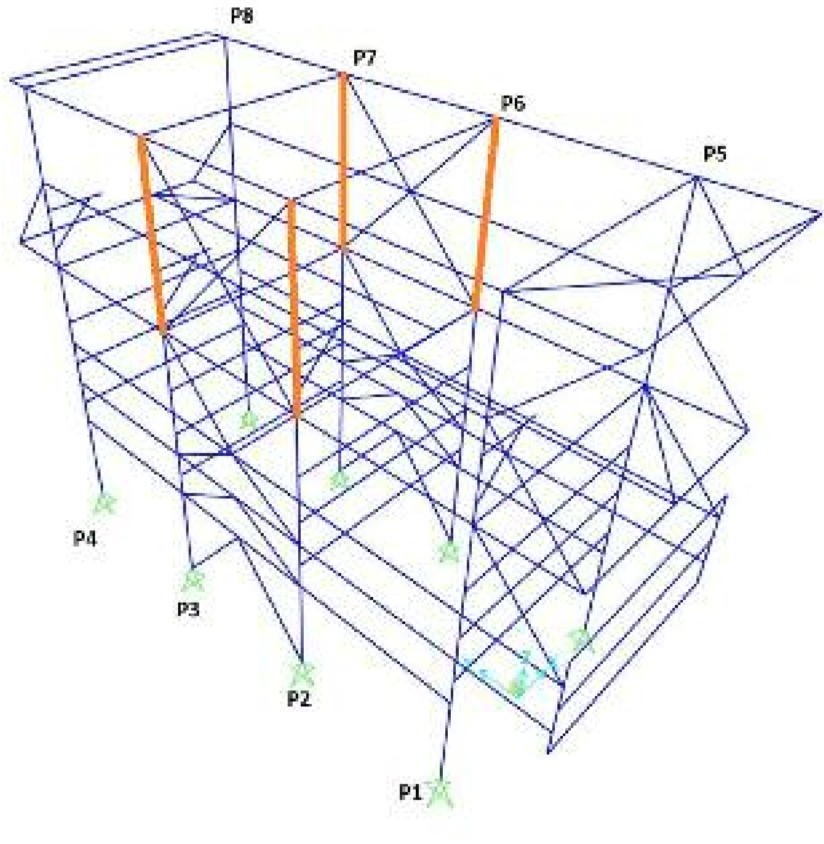

Figure B.11 - Schematic view of the columns which do not satisfy the safety requirement in terms of sectional strength (combination of axial force and bending moment with suitable overstrength factor for the moment resisting frame in the transverse direction)

2) Column strength in the longitudinal frames: in this case, the violation happens at the base level and it is connected to the requirements of capacity design in the case of concentric V- bracing system; the critical columns are graphically identified in Figure B.12.

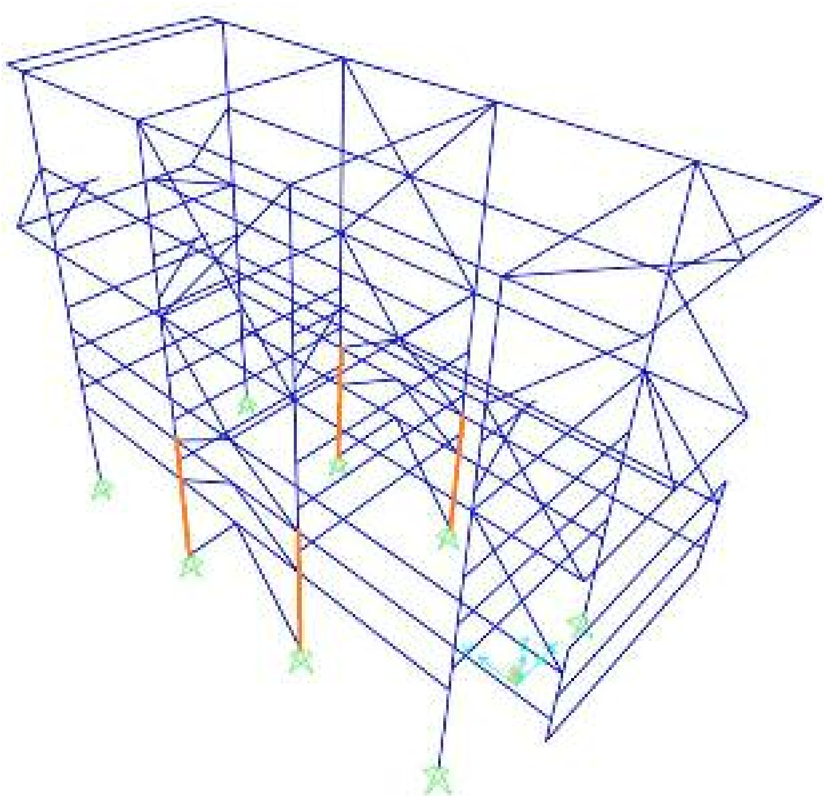

Figure B.12 - Schematic view of the columns which do not satisfy the safety requirement in terms of sectional strength (axial force with suitable overstrength factor due to the presence of dissipative V-bracing systems)

3) Diagonal bracings (Figure B.13): in spite of a positive compliance with strength and buckling requirements, it has been found a violation in the distribution of the overstrength coefficient: more specifically, the ratio between the maximum and the minimum overstrength value is 3.98 to be compared with the upper limit Passing to DLS, it is possible to verify a complete fulfillment of the requirements in the case of moderate earthquake. Conversely, for severe seismic actions, the interstorey drift is excessive for the base storey in the transverse direction (Figure B.14).

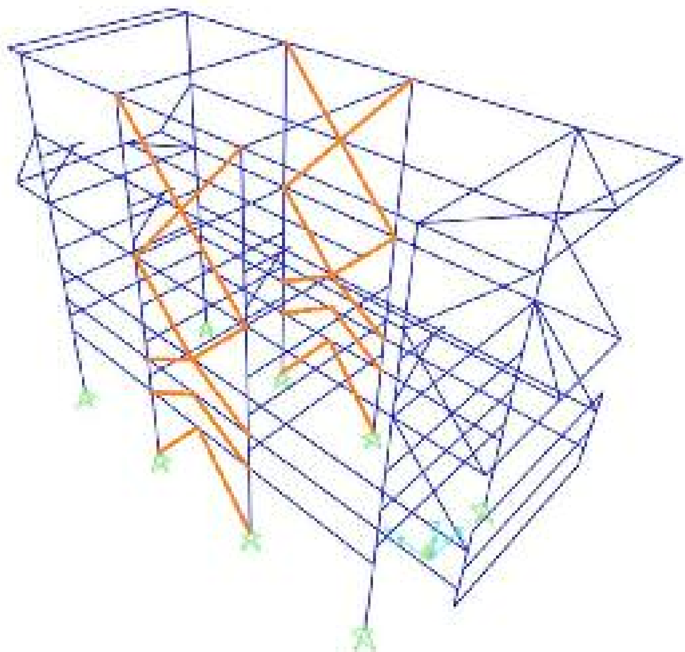

Figure B.13 - **Schematic view of the diagonal elements which do not satisfy the safety requirement in terms of overstrength homogeneity.**

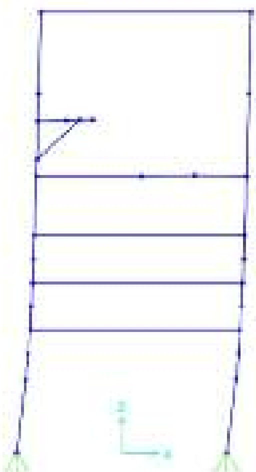

Figure B.14 - **Representation of the deformed configuration in case of severe earthquake: it is evident that the maximum interstorey drift is located at the bottom storey.**

4.2.4 Design suggestions for increasing the seismic performance

The violation of certain seismic requirements suggest the introduction of structural modifications, some of which have been already presented in the analysis of wind action. In particular, the introduction of a **horizontal bracing system** is beneficial for the collabouration of the transverse frame, and it is also useful in the seismic case because it involves a certain degree of "floor action" (despite the impossibility of introducing rigid floors at each storey level). The replacement of I shaped columns with **concrete filled hollow columns** is a good provision in order to increase the sectional strength: it is possible to verify that such a modification is sufficient to obtain the fulfilment of safety requirements for ULS with a good margin. Moreover, the composite columns are endowed with higher stiffness, so that it is possible to envisage an improvement of the safety assessment for DLS. Nevertheless, the stiffness increase is not enough in this case. In fact, account taken of the storey height = 4.6 m, one finds a limit threshold equal to 23.4 mm. Unfortunately, the seismic analysis yields an interstorey drift equal to 26.08 mm, which means a modest violation of the upper threshold.

A possible solution for the problem of excessive interstorey drift can be found by increasing the cross section of the transverse beam. The minimum section required is, in the present case, is HE500B, which entails a maximum interstorey drift equal to 22.88 mm. This provision is connected with a conspicuous increase of the structural weight: the original layout included HE360A, with mass per unit length equal to 112 kg/m; the new beams HE500B weigh 187 kg/m, with an increment of 67%. Additionally, the change of cross section is against the concept of standardization: view that the DLS violation happens only for severe earthquake, it would be desirable to keep the basic features of the standard design that is appropriate for most cases (i.e. moderate earthquake or lower). These considerations lead to the choice of a different stiffening strategy, based on the addition of structural element rather than on the replacement of beams. A possible solution is represented by **transverse bracing,** which however should not be so light if they had to satisfy the strength requirements for ULS [11]. In order to obtain an optimal solution in terms of structural weight, it is conceivable the introduction of a bracing system which is just used for displacement limitation, with a limited (or, in the best case, absent) effect on the ULS. Such an objective might be reached by the introduction of suitable mechanical fuses, for instance at the level of bracing joints, which exclude completely the diagonal elements in the case of horizontal actions higher than a certain threshold. However, it must be considered that this solution is connected with several difficulties, not least the economic impact of joint replacement after seismic events. It is better to envisage a bracing system where the compressed diagonal is expected to buckle under ULS actions, so that the most restrictive safety requirements can be circumvented and a lighter solution can be obtained. As a matter of fact, has it happens for the already discussed case of longitudinal bracing, this situation implies an additional bending action on the beam, which should be properly tackled.

The proposed transverse bracing is depicted in Figure B.15: the particular layout has been chosen in order to minimize the interference with the pipes and other plant devices, which run mainly in the longitudinal direction.

The achievement of a positive displacement assessment require really slender element, for instance a couple of UPN80 paired along the longer side at a distance of 25 mm. In this way, the interstorey drift at the bottom level is drastically reduced to 8.62 mm, thus respecting largely the safety limit. The relative displacement at the upper storeys are not changed with respect to the original layout, so that one can obtain a positive DLS assessment. Finally, it is necessary to check the ULS resistance of the beam, which is subject to the unbalanced vertical action as shown in Figure B.15: it is possible to verify that the increment of bending moment is considerable, though not sufficient to run out the plastic strength of the original beam. No change of the beam's cross- section is required, and the basic concept of standardization is preserved.

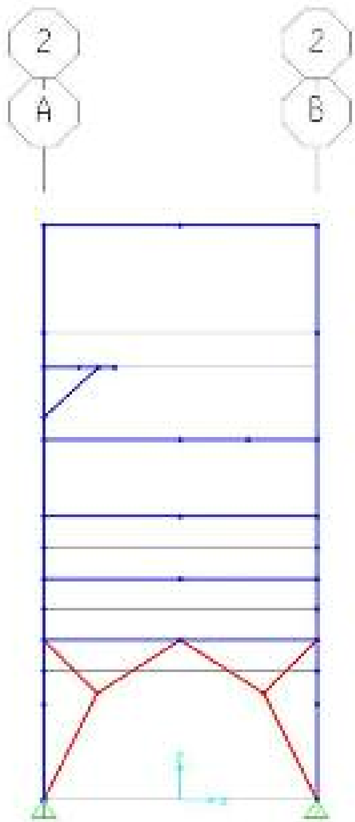

Figure B.15 - Proposed modification for the improvement of DLS performance: transverse bracing system.

POLITECNICO DI MILANO

Politecnico di Milano is a scientific-technological university which trains engineers, architects and industrial designers. The University has always focused on the quality and innovation of its teaching and research developing a fruitful relationship with business and productive world by means of experimental research and technological transfer.

Research has always been linked to didactics and is a priority commitment which has allowed Politecnico di Milano to achieve high quality results at an international level as to join the university to the business world.

Research activity moreover constitutes a parallel path to that formed by cooperation and alliances with the industrial system. The alliance with the industrial world, in many cases also favored by the Fondazione Politecnico and by Consortiums to which Politecnico belongs, allows the university to follow the vocation of the territories in which it operates and to be a stimulus for their development. The challenge which is being met today projects this tradition which is strongly rooted in the territory beyond the borders of the country, in a relationship which is developing first of all at the European level with the objective of contributing to the creation of a "single professional training market".

Politecnico takes part in several research and training projects collaborating with the most qualified European universities. Politecnico's contribution is increasingly being extended to other countries: from North America to Southeast Asia to Eastern Europe. Today the drive to internationalization sees Politecnico di Milano take part in the European and world network of leading technical universities and offers several exchange and double-degree programmes beside 2 three-year Bachelor of Science degree programmes, 10 Master of Science degree programmes, 12 Specialization Master's programmes and 24 Doctoral programmes which are entirely taught in English

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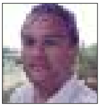
ANIMP is the Italian Association of Industrial Plant. Established in 1974, ANIMP is the "meeting centre" where Engineering Companies, Manufacturers of Plant Components and Universities may develop innovations and share common experiences to foster the construction of reliable and efficient industrial plants.

The joint goal of all members of ANIMP is to conceive and implement those improvements and changes that will enable them to respond quickly, with the right skills and technology to the challenges that world-wide Customers demand from industrial plants.

ANIMP Missions

- To represent and promote Italian plant industry (engineering, engineering and contracting companies, manufacturers of components for plants)
- To carry out events to increase the cultural and scientific knowledge, necessary for ANIMP Members to compete in the international market
- Indeed, through its Members, ANIMP is a highly qualified and prestigious vehicle of "Sistema Italia" in the world of the Plant Engineering & Supply Industry.
- ANIMP Members rely on the vast resource of more 95.000 highly skilled engineers and technicians.

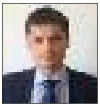
Task force (members)



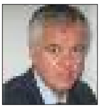
Luigi Anselmi
Head of Construction Operations
Tecnimont (Maire Tecnimont Group)

Raffaele Ardito
Assistant Professor - Department of Civil and Environmental Engineering
Politecnico di Milano

Angelo Balestrero
Senior Construction Manager

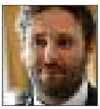


Nicola Careri
Research fellow - Dept of Management, Economics & Industrial Engineering
Politecnico di Milano



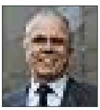
Paolo Cremonini
Director of Operations
Fagioli

Marco Di Gennaro
Support Services Section Head
Technip Italy



Luca Ferrazzi
Construction Methods Department Manager
Saipem

Gabriele Franco
Construction Director B.U. Oil & Gas
Rosetti Marino



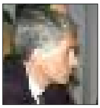
Alistar Gibb
Professor
ECI Royal Academy of Engineering

Mauro Mancini
Assistant Professor, ANIMP Construction section deputy Assistant Professor,
Dept of Management, Economics & Industrial Engineering **Politecnico di Milano**

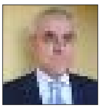
Andrea Manuli
Lead Civil and Structural Engineering
Technip Italy

Pierfranco Mocchetti
Civil & Structural Technical Manager
Tecnimont (Maire Tecnimont Group)

Alessandro Palmeri
Senior Lecturer in Structural Engineering
School of Civil and Building Engineering Loughborough University



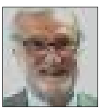
Federico Perotti
Full professor
Department of Civil and Environmental Engineering



Marco Spinelli
Head of Project Engineering and Technical Support
Tecnimont (Maire Tecnimont Group)

Paolo Trucco
Associate professor - Dept of Management, Economics & Industrial Engineering
Politecnico di Milano

Flavio Vitalini
Civil Engineer Manager
Foster Wheeler



Angelo Zucconi
Senior Project Construction Manager
Serding

Grafica: Paolo Sicignano

Realizzazione:

Stampa:

Companies involved