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Computer aided reinforcement design of RC structures

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Abstract. In this study, a design process for reinforced concrete structures using the nonlinear FEM analysis is developed. Instead of using the nonlinear analysis to evaluate the required performance after design process, the nonlinear analysis is applied before designing the reinforcement arrangement inside the RC structures. An automatic reinforcement generator for computer aided reinforcement agreement is developed for this purpose. Based on a nonlinear FEM program for analyzing the reinforced concrete structure, a smart fictitious material model of steel, is proposed which can self-adjust the reinforcement to the required amount at the cracking location according to the load increment. Using this tool, the reinforcement ratio required at design load level can be decided automatically. In this paper, an example of RC beam with opening is used to verify the proposed process. Finally, a trial design process for a real size underground RC LNG tank is introduced.

Keywords: nonlinear analysis; FEM; RC structures; computer aided design.

1. Introduction

With continuing development of fracture mechanics, nonlinear analysis can be used for the prediction of the performance of reinforced concrete structures during design process. If the predicted performance cannot satisfy the requirement, the design has to be improved and then, the nonlinear analysis must be reapplied. An ordinary design will repeat this kind of trial and error procedure several times. In this study, a design process for reinforced concrete structures using the nonlinear FEM analysis is developed. Instead of using the nonlinear analysis to evaluate the required performance after the design process, the nonlinear analysis is applied for the purpose of reinforcement arrangement. The nonlinearity of concrete cracking is considered in the analysis and the stress at cracking location will be transferred from concrete to steel after the cracking occurs. In order to carry this transferred stress, a special constitutive model of steel (smart fictitious material model) is adopted in the FEM program to avoid the yielding of reinforcing bar. The smart fictitious material model of steel can automatically adjust the reinforcement ratio at the cracking location according to the load increment. Finally, the reinforcement arrangement required at design load

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level can be automatically generated, consequently the effort and cost in the trial and error design procedures can be saved. In this paper, shear capacity design of an RC beam with openings is used to verify the proposed procedure, and a trail design process of a real size underground RC LNG tank is conducted.

2. Conventional process for reinforcment design

During the conventional design process of RC structures, except the cases where the reinforcement ratio can be decided by empirical experience, normally an elastic FEM analysis will be applied and then, the reinforcement design is carried out according to the principal tensile stress at different locations of the structure. After the reinforcement design of the structure has being completed, nonlinear analysis programs can be used to evaluate the performance of the structure, including checking the capacity and ductility. A typical design process for RC structures includes the following steps:

1. Choose the shape and dimensions according to experience and rules from design codes;
2. Establish all load cases and load combinations;
3. Perform linear analyses for all load combinations;
4. Arrange the reinforcement (usually according to the results of maximum tensile stresses);
5. Perform nonlinear analysis with accurate material behavior under the dominant load combinations up to failure to check the performance of designed structure;
6. Detail design of the reinforcement.

If the result from step 5 shows that the structures performance could not satisfy the requirement, usually it is called structure failure, we then must returen to step 3 to improve the reinforcement. The improvement can be derived from the results but usually it is difficult and special knowledge is

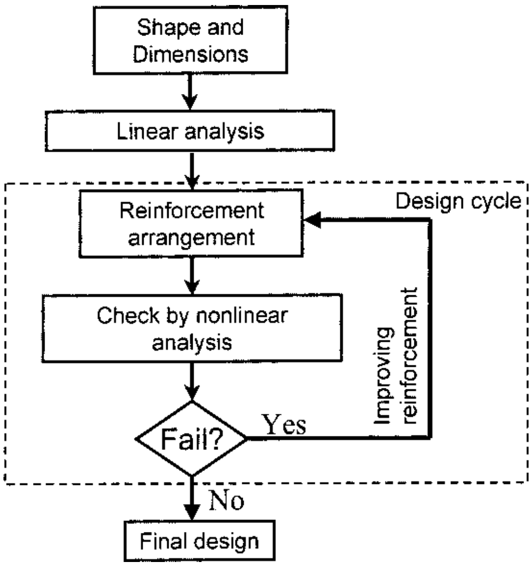

Fig. 1 Nonlinear analysis used as a checker in the design process of RC structure

required to explain the reasons causing the failure. Maximum stress will be meaningless after cracking, as stress relaxing occurs in nonlinear analysis. As the results from step 3 using a linear analysis cannot consider the cracking behavior of concrete, the initial design may need to be improved several times during the design cycles. The flow chart in Fig. 1 shows the attempts made in using the nonlinear analysis tool in the design process. Repeating the design cycle will increase the design cost because computation time of nonlinear analysis is considerable and a specialist is required to operate the software. Nonlinear finite element models are accurate and currently they are only used to check completed designs. As an example, a set of constitutive models for RC used in a nonlinear FEM code WCOMD (An, Maekawa, and Okamura 1997) is introduced in Fig. 2.

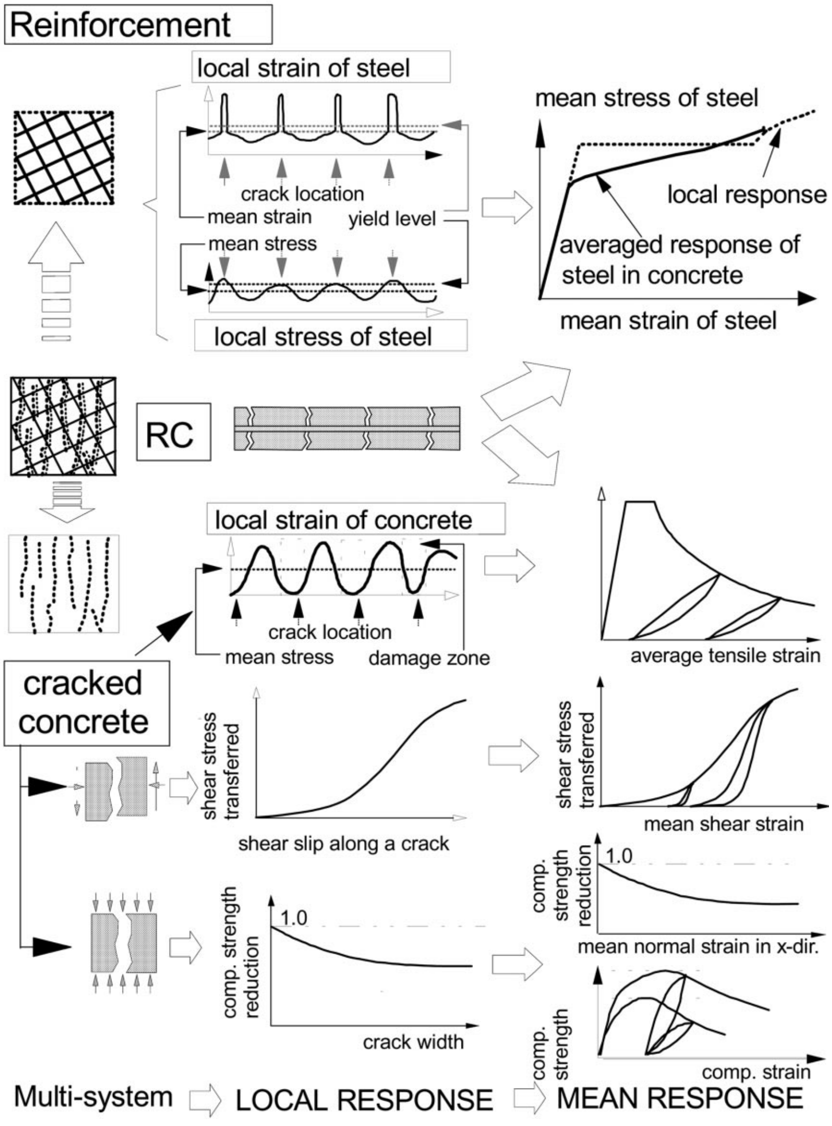

Fig. 2 Constitutive models for RC in a nonlinear FEM program

The difference between linear models and nonlinear models causes the gap between reinforcement design and performance checking. If the nonlinear behavior caused by cracking of concrete can be considered at the beginning of the design procedure, the initial design will be close to the optimized one and the required design cycles can be reduced. In this study, instead of using a linear analysis to arrange the reinforcement, the nonlinear finite element analysis is adopted as an automatic reinforcement generator. If the reinforcement is generated while considering the location and amount of the cracks, a good initial design can be made and time can be saved in the successive steps of the design process.

3. A smart fictitious material model for steel

The basic reinforcement design rule of RC structures is that the steel bars carry force under the design load and does not yield. After cracks occur in the RC structures, the stress carried by concrete at the cracking location will be transferred to the reinforcementas shown in Fig. 2. Usually, a nonlinear analysis will predict the cracking of concrete and reinforcement starts to carry the transferred stress according to the constitutive model of steel bars. Fig. 3 shows a typical stress-strain relationship of steel bar in RC specimen for nonlinear FEM analysis (Maekawa, Pimanmas, and Okamura 2003). During the conventional design process, the reinforcement amount (A_s) will be decided first. Then the nonlinear analytical method will be used to verify the yielding capacity F_y, using the model of steel.

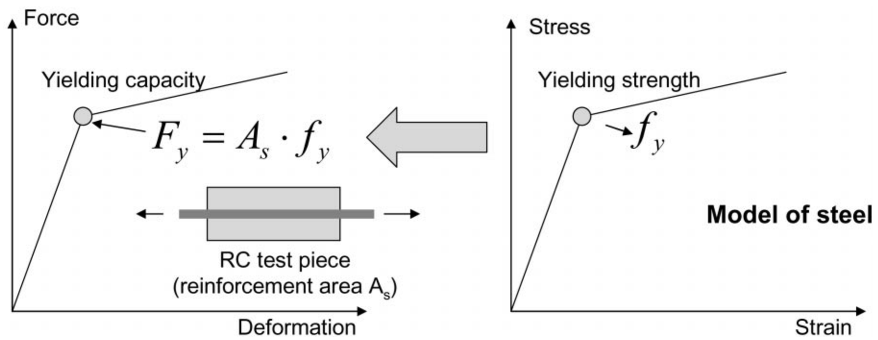

Fig. 3 Model of steel used for verification of yielding capacity of RC structure

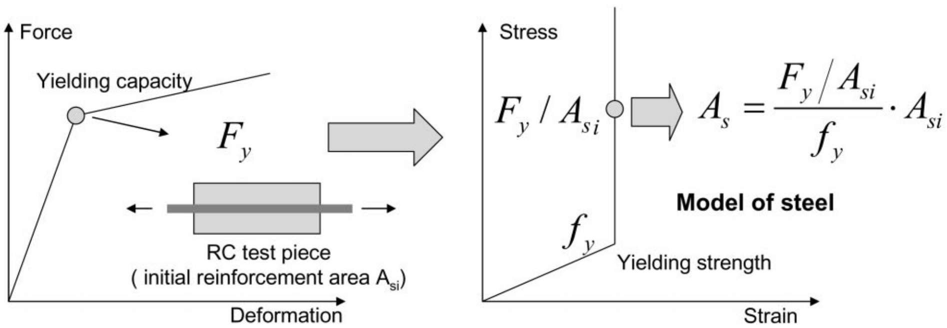

Fig. 4 Reversed process to decide steel amount from yielding capacity

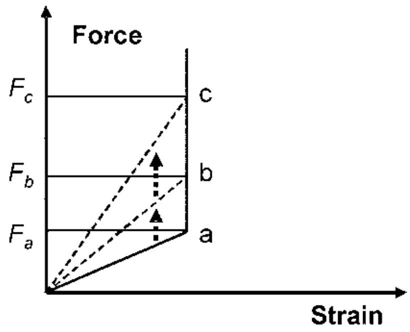

Fig. 5 A smart fictitious material model with strengthening behavior

In the case of generating an optimized reinforcement amount inside a RC structure, the process shown in Fig. 3 can be reversed. Knowing the design capacity, equal to the yielding capacity F_y, the corresponding force needed be carried by steel can be calculated, and then, the required amount of steel (A_s) can be converted, as shown in Fig. 4.

During the process of increasing the load applied to the RC structure up to design load level, initial cracks may happen inside the concrete, and stresses will be re-distributed. The cracked locations with very low reinforcement ratio start to yield. If we want the reinforcement to carry the transferred force f_b without yielding, we have to strengthen it locally, for example, increase the reinforcement ratio. Subsequently, the reinforcement is strengthened to point *b* and the carried force increased to f_b (Fig. 5). When the transferred force is up to f_c according to the loading increment, once more the material is strengthened to point *c*. The subsequent strengthening of the reinforcement can be replaced by the vertical line (a-b-c) in Fig. 5. Thus, strengthening behavior appears for the reinforcement (Hoogenboom 1998).

Strengthening behavior is the opposite of plastic behavior. It is very stable in load-controlled computations and in only one design cycle, the final distribution of forces can be obtained. It is different to the usual nonlinear materials. A usual nonlinear analysis shows that the structure fails but does not indicate how to improved it. This smart fictitious material model with strengthening behavior will automatically increase the load carrying capacity at the locations where necessary, this leads to a good initial design and can satisfy the finial nonlinear analysis checking with ease.

During FEM analysis, by switching the steel model in the existing nonlinear FEM program into this smart fictitious material model, P_{NEW} the reinforcement ratio needed to carry the force at each element can be calculated as follows:

$$p_{NEW} = \left(\frac{F_b}{F_a}\right)p_{initial} \tag{1}$$

$p_{initial}$: Initial reinforcement ratio set for each element;
f_b : force needed to be carried at a required load level;
f_a : yielding force can be calculated as,

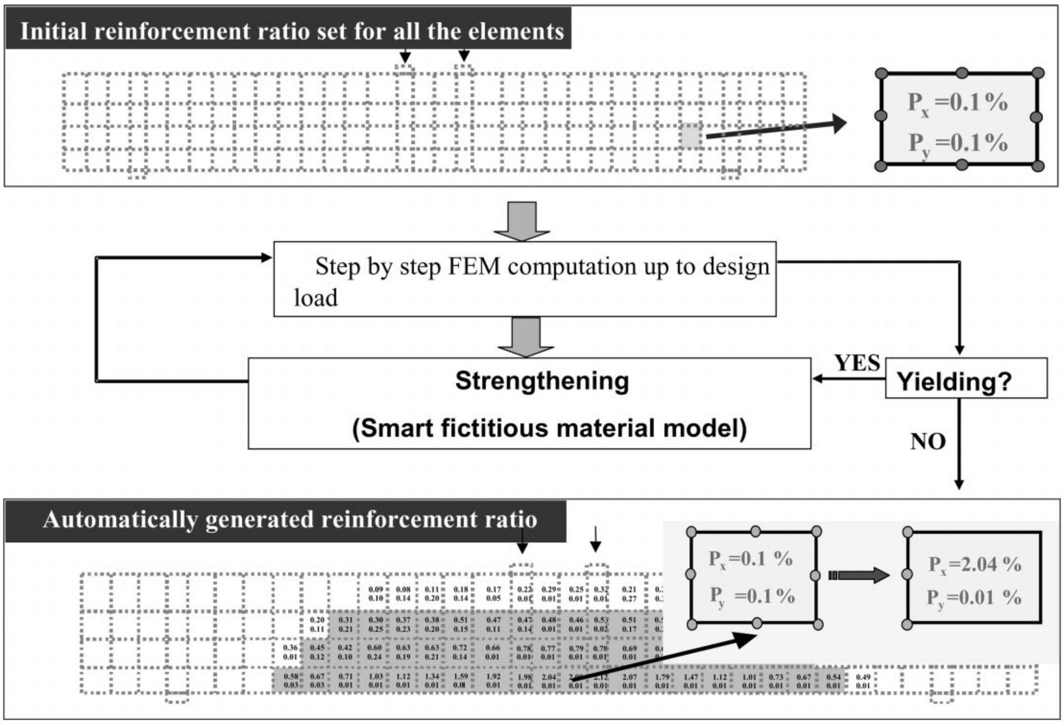

Fig. 6 Flow chart for automatically generating of reinforcement ratio in RC structures

$$F_a = p_{initial} \cdot A \cdot f_y \tag{2}$$

A : element section area,
f_y : yielding strength of steel bar.

The constitutive models for concrete in tension, compression and shear are summarized in Fig. 2. These models are the same as that installed in the nonlinear FEM program for checking the completed design.

The reinforcement generating process (Fig. 6) can be carried out as follows:

1. Set initial reinforcement ratio after deciding shape and dimensions of the RC structure;
2. Perform the generator under design load for the output of reinforcement ratio;
3. Summarize the output reinforcement ratios from all load combinations.

4. Option of including experience from user

After transforming a real RC structure into a finite element model, the reinforcement generator program will strengthen the elements wherever cracking occurs and increase reinforcement ratio automatically. The result supplies a map of reinforcement ratios in all the elements and experience is needed to change this map into a detailed reinforcement arrangement (Fig. 7(a)). Here, an option is given to include the engineering experience into the reinforcement generation. It allows the user

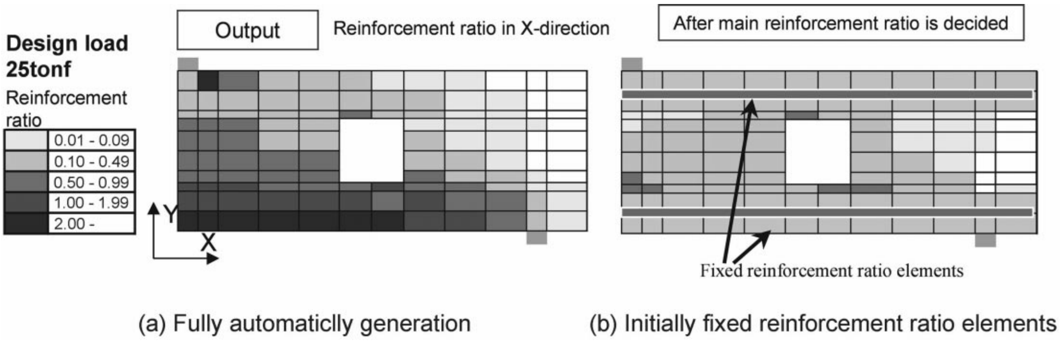

Fig. 7 Two kinds of reinforcement ratio map (X-direction) generated for design load

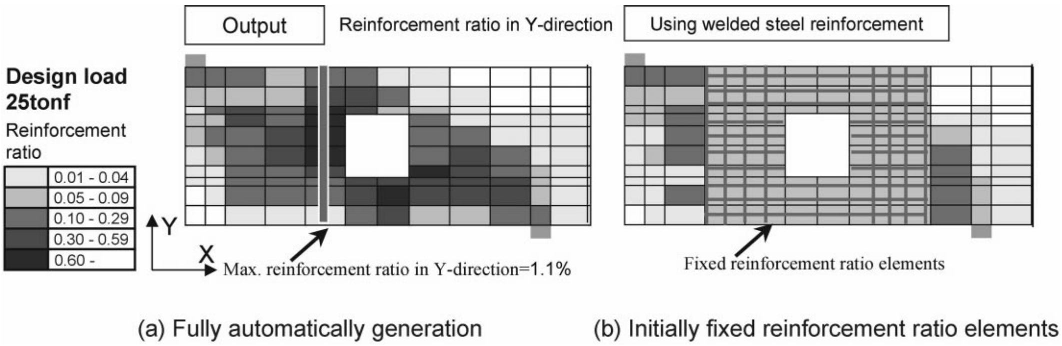

Fig. 8 Two kinds of reinforcement ratio map (Y-direction) generated for design load

to initially set the fixed reinforcement ratio elements, and for these elements, the reinforcement ratio will not be automatically changed during the computation. This option can be used in the case where the user has decided part of the reinforcement arrangement and allows the computer do the other parts.

Fig. 7 gives an example of design of a beam with an opening in the span. The bending capacity can be easily predicted by deciding the main reinforcing bars. In this case the fixed reinforcement elements will be used to represent the decided main reinforcing bars, and then after computation, the result map of reinforcement ratio becomes much more reasonable.

Fig. 8 gives the results for shear reinforcement design of the beam with an opening. According to the resulting map of reinforcement ratio, it is easy to choose a single layer of steel bars to satisfy the required reinforcement ratio of 1.1% (Fig. 8(a)). However, in reality, welded steel mesh is often used as the reinforcement of openings. In this case, the reinforcement ratio surrounding the opening can be decided first, using fixed reinforcement ratio elements to carry out the computation for other parts (Fig. 8(b)).

The proposed concept allows a new optimization design procedure based nonlinear analysis, using an automatic reinforcement generator in the first stage of determining the initial design plan (Fig. 9).

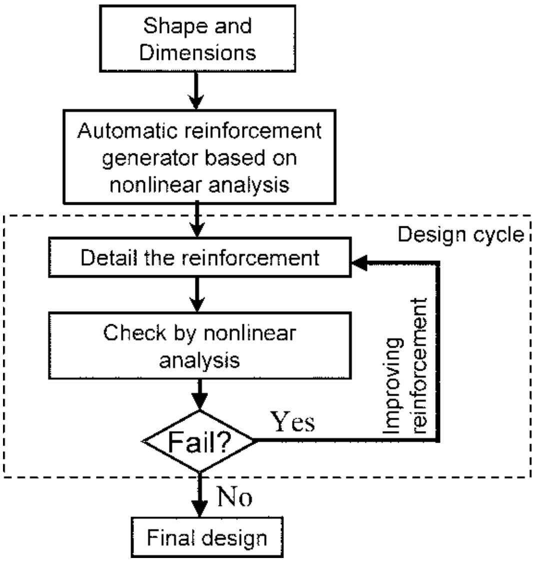

Fig. 9 Nonlinear analysis used also as a generator in the design process of RC structure

5. Experimental verification

An experiment has been conducted by following the new design process. A beam with openings has been reinforced according to the output reinforcement ratio automatically generated (Fig. 10). The purpose of this experiment is to check the shear capacity of this beam, that is, whether the automatically generated reinforcement in Y-direction is enough to carry the shear force.

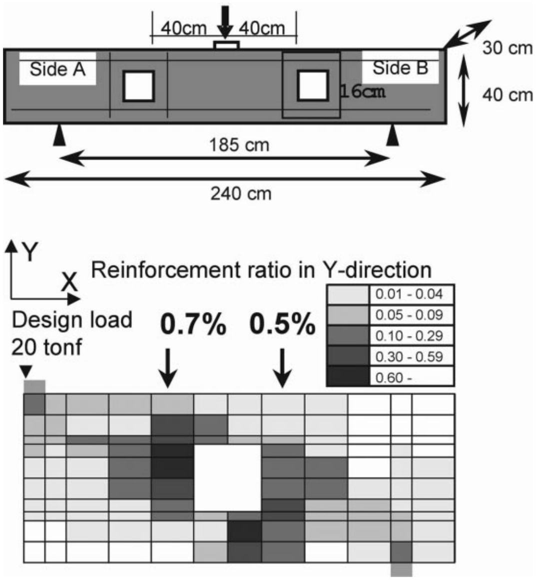

Fig. 10 Shape and dimensions of the beam and the output reinforcement ratio map (Y-direction)

Design shear load is set as 200 KN, which is much lower compared to the bending capacity of this beam. The main reinforcement ratio is decided before computation and the fixed reinforcement ratio option is used. The output reinforcement ratio map for 200 KN is also shown in Fig. 10.

Considering the output results of reinforcement ratio, 3 steel bars with diameter of 10 mm will satisfy the design load. Here, two types of arrangement of steel bars are adopted. Type A, normal shear reinforcement type is put into side A of the beam, and Type B, same reinforcement amount but surrounding the opening, is put into side B (Fig. 11). The detail of reinforcement arrangement for side A is shown in Fig. 12. During the experiment, side A of the beam failed first but was strengthened by steel bars (Fig. 13). Then loading was continued until the side B failed.

Fig. 14 shows the experimental load-deflection relationship. The capacity for side A is 224 KN

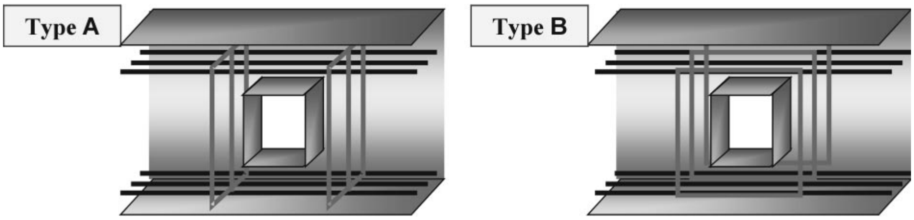

Fig. 11 Two types of shear reinforcing bars used to strengthen the opening

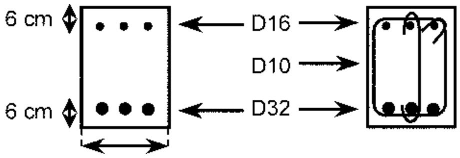

Fig. 12 Detail of reinforcement (Side A)

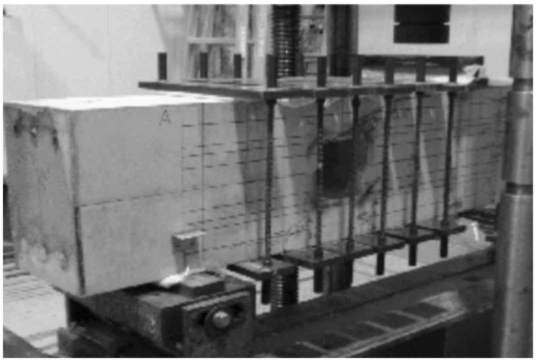

Fig. 13 Strengthening the failed Side A

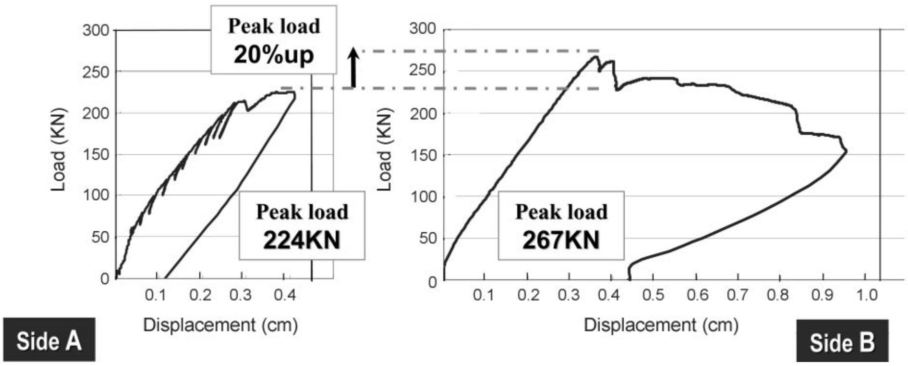

Fig. 14 Load-deflection (center) relationship of the beam

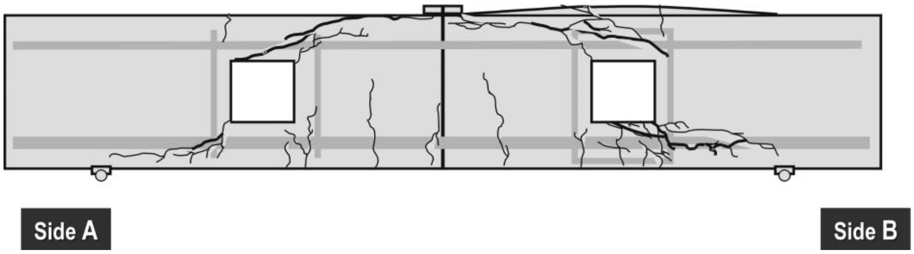

Fig. 15 Crack patterns for two sides of the beam

and for side B is 267 KN. Both satisfy the design load. Side B is much stronger than side A as the horizontal part of shear reinforcement of Type B contributes significantly. It can be noticed in Fig. 15, the crack pattern for Side B shows the cracks on the top and bottom of the opening are distributed because of the existence of horizontal steel bars. This result confirmed that, after the output of automatically generated global reinforcement ratio, the engineering judgment of reinforcement detail is necessary, especially for cracking control.

6. Application to a trial design process of large LNG tank

During the design process of underground large scale LND tank, nonlinear FEM code becomes into a powerful tool for evaluating the safety under complex load conditions, including temperature changing, water pressure and soil movement under earthquake load. However, the initial reinforcement design is usually proposed by using the linear elastic analysis, with results in the required amount of reinforcing bars being over estimated, and difficulty is produced in construction. Fig. 16 shows the scale of a real reinforced concrete underground LNG tank, and the material properties are summarized in Table 1.

Here the proposed automatic design process is used to generate the reinforcement ratio in the real

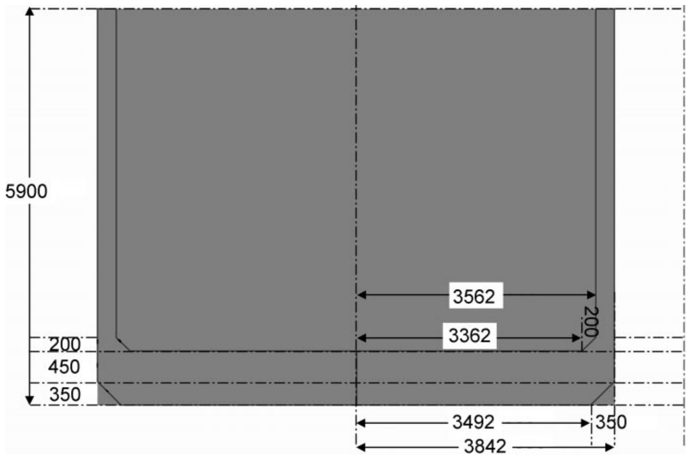

Fig. 16 Shape and scale of a LNG tank (Axial section, unit: cm)

Table 1 Material properties of the RC LNG tank

Wall (side)		Slab (bottom)	
Concrete	Steel	Concrete	Steel
$f'_{ck}=60(\mathrm{N/mm^2})$	$f'_y=345(\mathrm{N/mm^2})$	$f'_{ck}=24(\mathrm{N/mm^2})$	$F'_y=345(\mathrm{N/mm^2})$
$E_C=35(\mathrm{kN/mm^2})$	$E_S=200(\mathrm{kN/mm^2})$	$E_C=25(\mathrm{kN/mm^2})$	$E_S=200(\mathrm{kN/mm^2})$
$\alpha_c=1.0\times10^{-5}/^{o}\mathrm{C}$	$\alpha_s=1.0\times10^{-5}/^{o}\mathrm{C}$	$\alpha_c=1.0\times10^{-5}/^{o}\mathrm{C}$	$\alpha_s=1.0\times10^{-5}/^{o}\mathrm{C}$

size underground RC LND tank. Two typical loading cases has been used to demonstrate the reinforcement design process:

- **Case 31**, inner liquid pressure;
- **Case 41**, outside pressure (uplift loading + water pressure + soil pressure).

The design loading values and the mesh for automatic design process as well as nonlinear FEM evaluation are shown in Fig. 17. As the shape of the LNG tank is a round circle, an axial-symmetry model is used for FEM computation.

The criterion of the automatic reinforcement generating process is that, yielding of reinforcement just happens under the design loading values. The initial reinforcement ratio is set as 1% for all the directions inside the RC tank. The proposed reinforcement design, based on the automatically

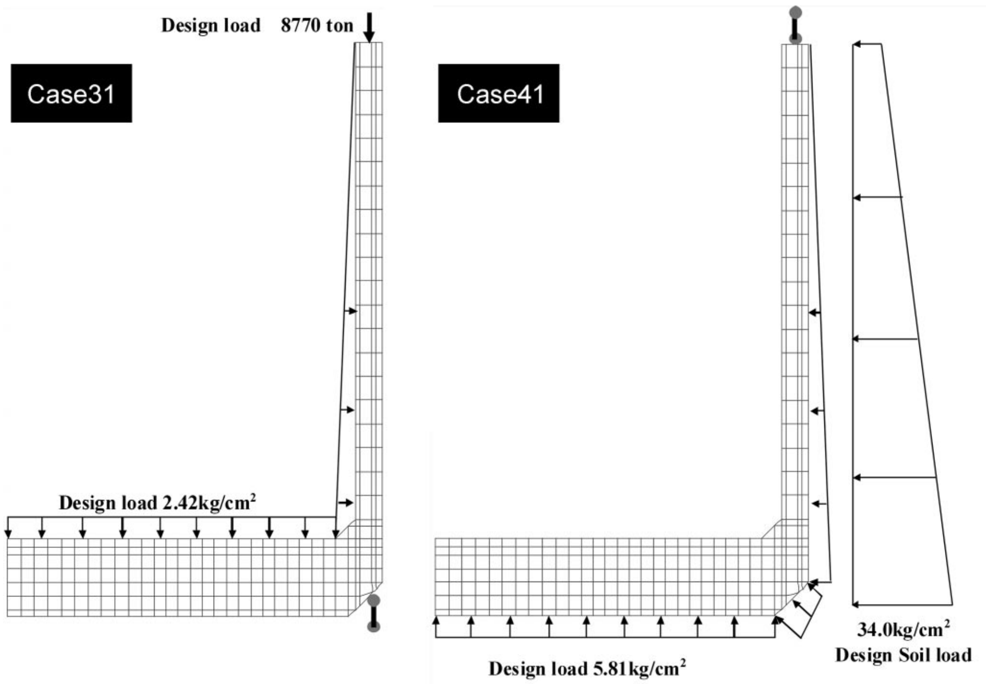

Fig. 17 FEM computation model and design loading cases of the LNG tank

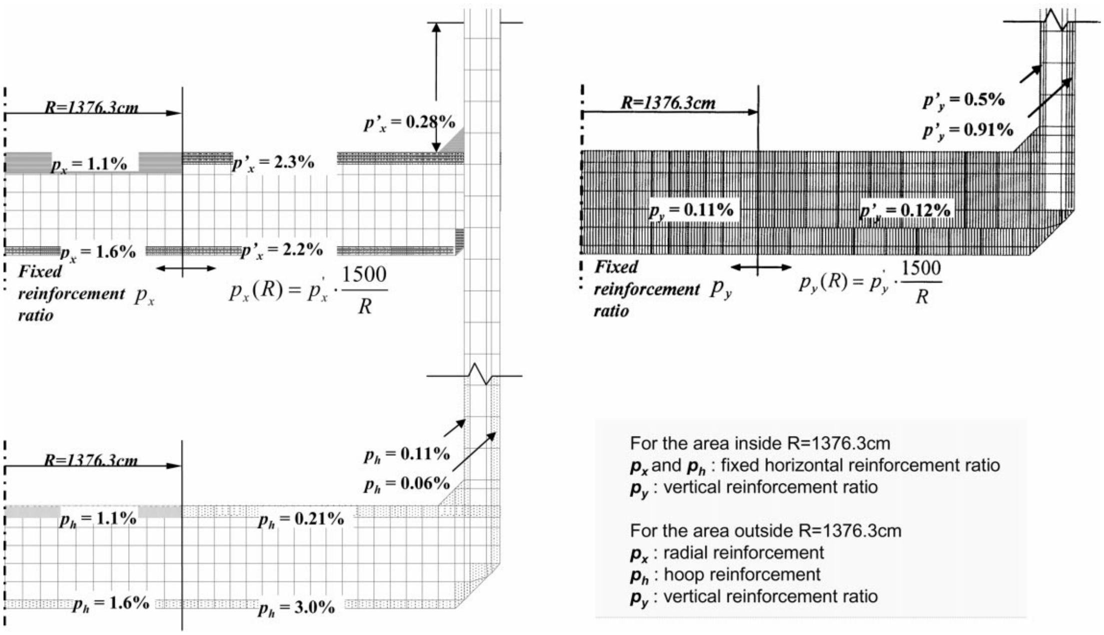

Fig. 18 Proposed reinforcement ratio based on the automatically computed results

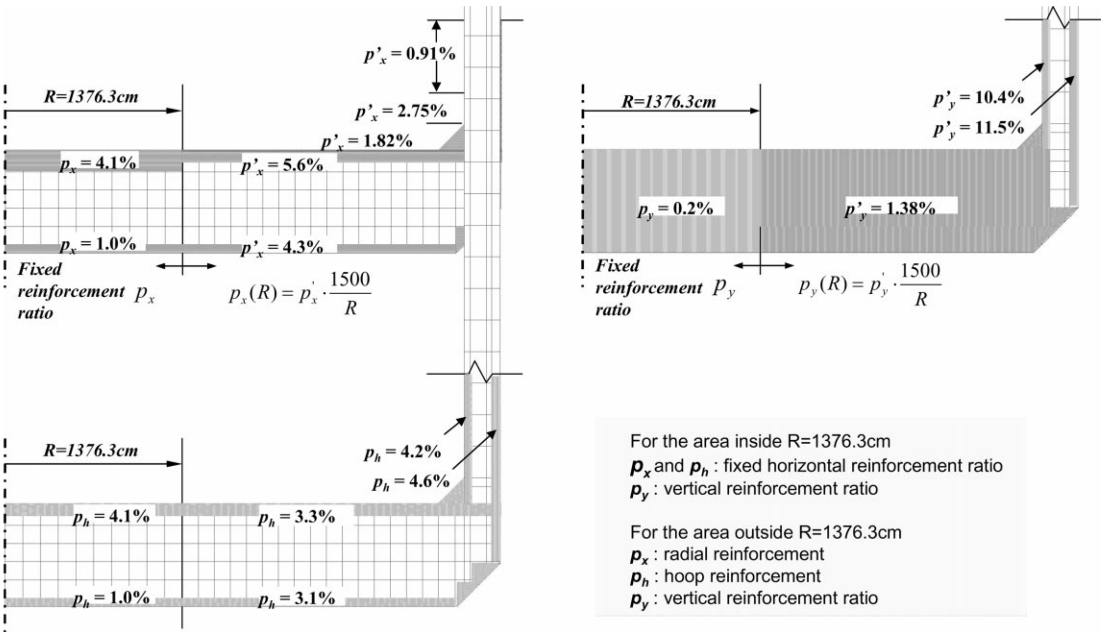

Fig. 19 Proposed reinforcement ratio based on the linear FEM analysis

computed reinforcement ratio results is shown in Fig. 18.

As a reference, the reinforcement design, decided by tensile stress results from linear FEM analysis, is shown in Fig. 19. From the comparison of these two design proposals, the difference of

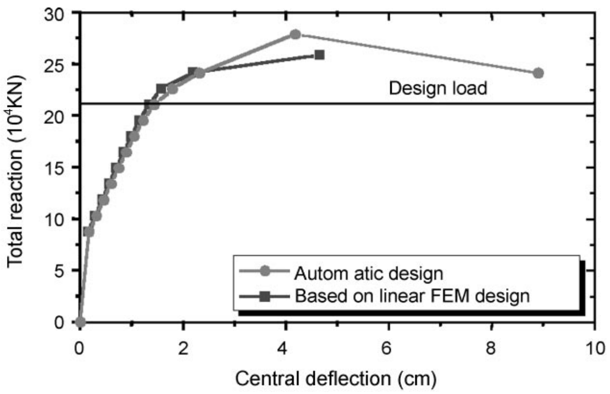

Fig. 20 Load-deflection results from the nonlinear FEM analysis (CASE31)

reinforcement ratio can be noticed. The reinforcement ratio proposed by the automatic process is extensively less than the value based on the linear 3D FEM analysis.

Because the proposed reinforcement generator includes the effect of concrete cracking during the design process, the stress concentration in the linear FEM analysis can be avoided. In this case, the stiffness of cracked RC structure is more flexible and the increasing stress can be transfer to the other part of the structure. On the other word, considering the cracks of concrete can make use of the reinforcement more effective.

The structural behavior of the proposed designs can be evaluated by nonlinear FEM analysis. By using the nonlinear FEM code for RC structures, axial-symmetry analyses are carried out to check the capacity and deformability of the designed LNG tank under the loading cases of Case31 and Case41.

In Fig. 20, the capacity and deformation results of the LNG tank with two different reinforcement arrangements for Case31 are compared. It can be confirmed that both of the automatic reinforcement generation and the linear FEM design result can satisfy the required design capacity. The yielding result map (Fig. 21) at design loading stage shows that, in the case of the automatic reinforcement generation design, the first yielding of reinforcement just starts at the inner side of the corner, where the stress concentrates under the inner liquid pressure (Fig. 22(b)). On the other hand, no yielding happens at the design loading stage in the evaluation of the design based on the linear FEM result.

In Fig. 23, the capacity and deformation results of the LNG tank with two different reinforcement arrangements for Case41 are compared. It can also be confirmed that both of the automatic reinforcement generation and the linear FEM design result can satisfy the required design capacity. By comparing the deformation of RC tank under inner and outside pressure (Fig. 22), the different critical locations of loading Case31 and Case41 can be noticed. In the case of inner liquid pressure, the tensile stress concentration happens at the inner side of the bottom corner. On the other hand, in Case41, outside water and soil pressures cause the critical location to be at the bottom of the wall, just upon the corner. Using the reinforcement design based on the linear FEM results, the required amount at this location is very high (shown in Fig. 19), which results a stiffer structural behavior. The proposed reinforcement ratio based on automatic process at this location is much smaller, which results widely distributed reinforcement yielding. The yielding result map (Fig. 24) at design

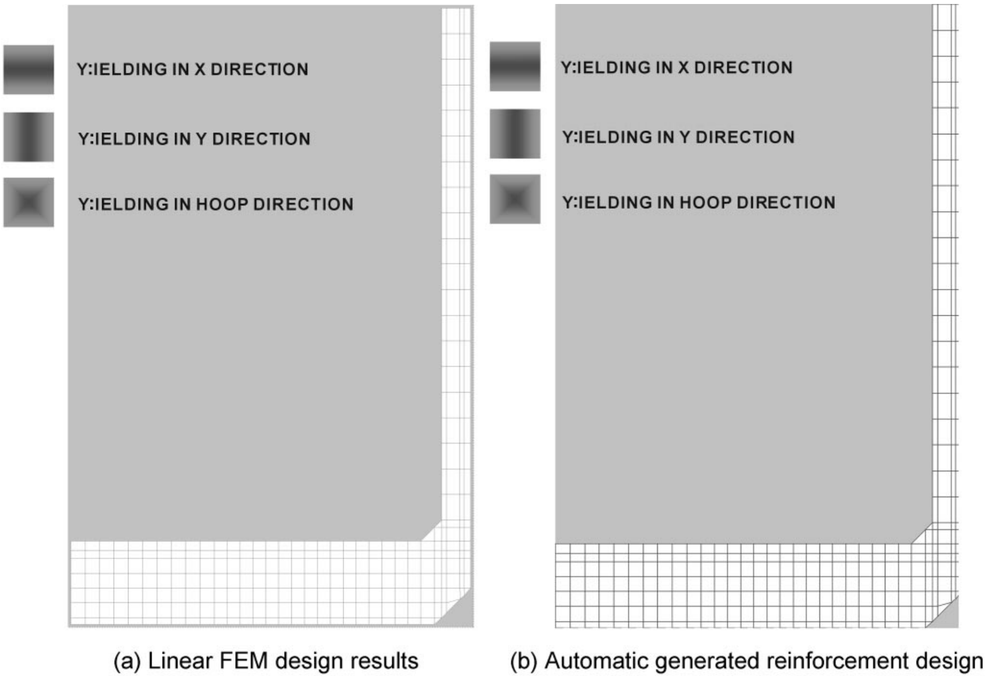

Fig. 21 Yielding map of reinforcement at design loading of Case31

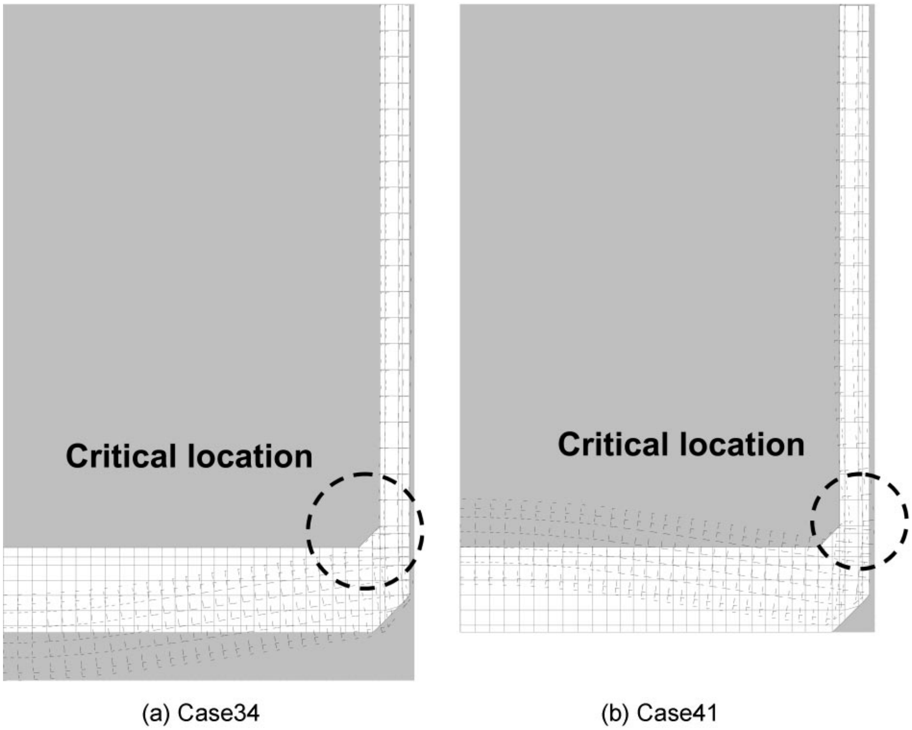

Fig. 22 Typical deformation and critical location of the RC LNG tank

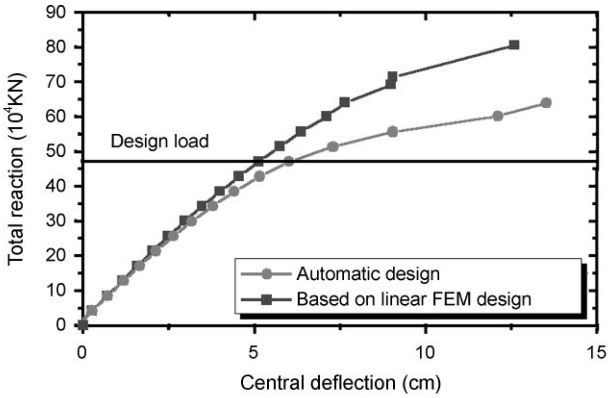

Fig. 23 Load-deflection results from the nonlinear FEM analysis (CASE41)

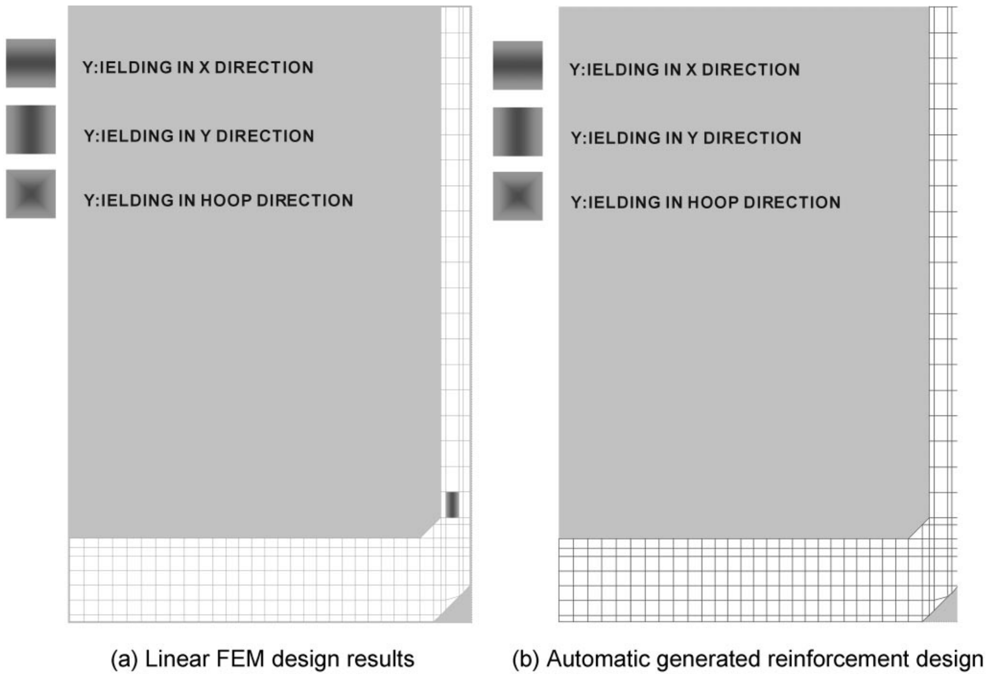

Fig. 24 Yielding map of reinforcement at design loading of Case41

loading stage shows that, in the case of the automatic reinforcement generation design, the yielding of reinforcement happens at several areas in the tank. However, yielding only happens at critical location in the evaluation of the design based on the linear FEM result.

The zoom in detail of crack patterns of the corner of LNG tank at failure stage of Case41 is shown in Fig. 25. Because of the high reinforcement ratio at the critical location and stiff structural behavior, the design based on the linear FEM result results in serious damage at the corner of the LNG tank. On the other hand, the automatic reinforcement design process gives a flexible structure, and the damage is much slighter at the corner location.

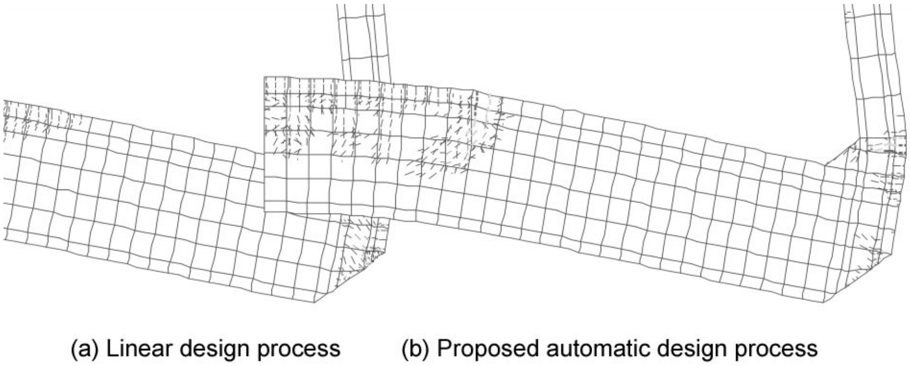

Fig. 25 Zoom up of crack patterns at the corner of LNG tank at failure stage (Case41)

These differences verified that the balance of reinforcement arrangement provide a flexible structure, and the automatic reinforcement design process considering cracking of concrete gives a simply and effective way to generate the balance of reinforcement.

7. Conclusions

An automatic reinforcement generating tool for global level reinforcement design, based on nonlinear analysis, has been developed for the design process of RC structures. The smart material model with fictitious strengthening behavior is adopted to generate the reinforcement automatically according to the applied force. An RC beam with opening has been designed by using the proposed process and the experimental results proved the performance. Using the proposed automatic reinforcement generator, a trial design process is carried for a real size underground RC LNG tank. In comparison with reinforcement design based on linear FEM results, the proposed design process can provide a smaller reinforcement ratio and a flexible structural behavior.

The experimental results for different layouts of steel bars shows that the detail of reinforcement, such as anchorage and confinement, will affect the behavior of the RC structure. In further study, the application of the proposed automatic generator to detail reinforcement arrangement, such as for the corner of the LNG tank, will be examined. This generator will be extended to 3D reinforcement design in the near future.

References

An, X., Maekawa, K. and Okamura, H. (1997) "Numerical simulation of size effect in shear strength of RC beams", *J. of Materials, Concrete Structures and Pavements, JSCE*, **35**, 297-316.

Hoogenboom, P.C.J. (1998) "Discrete elements and nonlinearity in design of structural concrete walls", Dissertation, Delft University of Technology,

Maekawa, K. and An, X. (2000) "Shear failure and ductility of RC columns after yielding of main reinforcement", *Engineering Fracture Mechanics*, 65, 335-368.

Maekawa, K, Pimanmas, A. and Okamura, H. (2003), *Nonlinear Mecganics of Reinforced Concrete*, Spon Press, NY.