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Staged analysis of RC frame retrofitted with steel braces in low and medium-rise buildings

Made Sukrawa[a,]*

[a]*Civil Engineering Dep. Udayana Univ. Bali -Indonesia*

Abstract

The emerging concept of sustainable construction has lead researchers and practicing engineers to preserve and strengthen existing structures to minimized use of materials and energy associated with it. As a result, many retrofitting techniques for RC frame structures has been proposed and applied as opposed to reconstruction. Among the techniques to increase the seismic load carrying capacity of existing structures, the use of steel braces is very popular and relatively easy to work on. This paper try to consider construction and loading stages in the analysis of earthquake responses of existing RC frame retrofitted with steel braces for low and medium-rise buildings. For that purposes, RC frames of 3, 5, 8, and 10 story typical office buildings were designed consisting of four 3-bays frames in each direction. The chevron A and X-shaped braces were added to the middle bay of the exterior frames to minimized functional changes of the building. Analyses of 3-D models show that the earthquake response of RC frames with A and X steel braces are significantly stiffer and stronger than the original bare frames. The reinforcement requirement in the frames also reduced significantly with the addition of braces. Compared to conventional analysis, staged analysis using cracked section produce larger deformation and forces on the frames, and accordingly, should be used in the analysis to have more accurate result and safer design.

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Keywords:RC frame; seismic retrofit; steel braces; staged analysis; low and medium-rise buildings

1. Introduction

Many low and medium-rise buildings up to 10 stories high are built using reinforced concrete moment frame (RC frame) structures owing to its competitive cost compared to using steel structures, especially in the areas where

* Corresponding author.
E-mail address: msukrawa@yahoo.com

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labors are available at affordable cost and time for construction is not critical. The rigid beam to column joint makes the lateral stiffness of RC structures high enough to resist earthquake load without any additional lateral stiffener such as shear walls or braces. It also requires less maintenance which makes RC frame a popular choice for low and medium-rise structures. Compared to steel structure, however, RC frame is less ductile which make its performance under stronger earthquake less favorable.

The revised earthquake code for structural design usually requires more ductile performance of the structure to prevent sudden collapse. It also has new earthquake map of ground acceleration based on more earthquake records that differ significantly from the older code. This is true for the case of Indonesian new code of earthquake design. Some areas which, in the older code [1] were specified as low to moderate seismic risk, have changed to seismic design category of D or E in the newer code [2] that require stronger and more ductile performance. Accordingly, many RC structures built in accordance to the older code may not be strong and ductile enough to satisfy the requirements of the newer code. In such a case, the structures need to be strengthened as opposed to rebuilding, because retrofitting an existing structure requires much less resources and energy, and produce less waste materials.

The concept of minimum interruption of building function and operation is also essential from the owner's perspective that has to be considered in choosing the retrofitting method. Many techniques have been proposed and used to retrofit existing RC moment frame structures, including strengthening of the weak frame elements or adding new structural elements to increase strength and deformability of the structures. In the first technique, columns and beams are strengthened by enlarging its dimensions or by jacketing using steel, carbon fiber, or other high strength materials. In the second techniques, new structural element can be added to the existing frame such as concrete walls, wing wall, masonry infill wall, steel brace frame, cables or its combination [3, 4, 5]. Each technique has its advantages and drawbacks. Addition of new walls is among the techniques that very effective to increase the strength and stiffness of existing structures. This technique however, will require a lot of efforts to transport large quantity of material to the higher floor level that may disturb and interfere the building operation.

Addition of steel braces into one bay of exterior frames will require less effort to satisfy the concept of minimum interruption because it can be done from the outside of building. It is however, will change the aesthetics of the building. A careful choice of brace types will strengthen the structures without sacrificing its beauty. In this study, addition of steel braces of chevron "A" shaped (A brace) and diagonal X-shaped (X brace) type to existing structures of 3, 5, 8, and 10 story office buildings are chosen to investigate the effectiveness of the techniques to strengthening existing structures.

Preliminary study on the effect of adding steel braces of chevron A shape and X-shaped types to existing 2D RC frames of 3, 4, and 5-story has been done [6]. It was found that the braced frames are almost twice stiffer than the bare frame and the reinforcement requirement reduce as much as 7.9% for columns and 18.8% for beams. The significant increase in stiffness and strength of RC frame with additional steel braces has been shown trough a number of experimental works [7, 8, 9, 10]. The technique also works well to strengthen non ductile RC structures [11].

For the case of strengthening an older RC frame structures, the condition of the structure is generally not good. Some cracks may exist and the structure already underwent deformation due to vertical and probably lateral loads before the strengthening technique applied. These existing conditions are very seldom taken into consideration into the analysis. Often time the analysis was performed conventionally as if the retrofitted structure is new, ignoring the existing deformation and cracks. With the advance of software in structural analysis and design, conditions of existing structure to be retrofitted can be taken into account by performing non linear staged analysis in which the deformed structure at previous stage is used as initial condition for the next stage [12, 13]. The cracks in frame members should also be considered in the lateral displacement analysis by modifying the section properties of frame [14].

In the current study, the RC frame with additional steel braces model is extended to 3D structure to include the contribution of the un-braced frames and the floor slab structures. It is also extended to 8 and 10-story building to cover its application on medium-rise building. The RC structures are considered already deformed and cracked prior to the application of the braces. Accordingly, staged analysis was performed using non linear staged construction analysis available within SAP2000 using cracked sections properties. In addition, static push over analysis was done to check if the braced frames perform better than that of the bare frame under seismic loading.

2. Methods

For the purpose of investigating the effectiveness of adding steel braces to strengthen existing RC frame structures, hypothetical office buildings of 3, 5, 8, and 10-story were assumed to be designed and constructed as open frame structures (OFn). The 'n' denotes the number of story. The 3-bay frames structures were then redesigned with additional steel braces of chevron "A" shaped (BFnA) and diagonal X-shaped (BFnX) in the middle bay of each exterior frames. The plan of the structure is as shown in Fig. 1 followed by the elevation of 3-story open frame (OF3) and braced frames (BF3A and BF3X) in Fig. 2. The span length of beam is 6 meters and the story height is 3.5 meters. The properties of materials for all frame structures are the same. A 25 MPa concrete with 400 MPa rebars were used for the RC frames and 240 MPa steel was used for the braces.

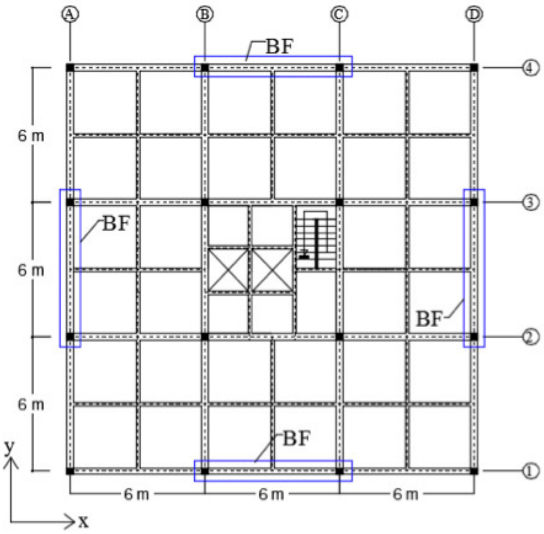

Fig. 1. Plan of the office building showing floor structures and location of braces (BF)

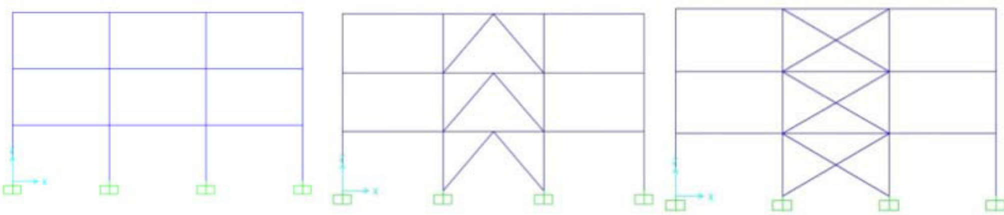

Fig. 2. Elevation of 3-story frames: OF3 (left), OF3A (center), OF3X (right)

The dimensions of the open frame elements were determined in such a way that the reinforcing steel required for the beams and columns lies between minimum and maximum allowed by the Indonesian concrete codes [15] which is very similar to the ACI code [14]. Table 1 shows the dimension of the beams and columns for all of the open frame structures. Secondary beams of 200x400 mm were used to stiffen the 120 mm thick floor slab.

The office building was designed for live load of 2.45 kN/m^2 for the floor and 0.98 kN/m^2 for the roof. For the seismic loading, static equivalent load was used based on Indonesian seismic code [2]. To check the accuracy of lateral loading calculation, auto lateral load feature of SAP2000 was also run and the results were compared internally.

All of the open frame models were analyzed and designed to conform to the recent seismic and concrete codes [2, 15] for strength and stiffness. Steel braces were then added in the mid span of exterior frames assuming pin connection between the braces and the RC beams and beam to column joints. The joint at the crossing of X braces is fixed. The braced frame structures were then analyzed and designed with the same loading as those of the open frames to be compared to the original open frames in term of story drift and reinforcing steel areas.

Table 1. Dimension of the frame elements (mm)

Level	3 Story		5 Story		8 Story		10 Story	
	Beam	Column	Beam	Column	Beam	Column	Beam	Column
1	300x500	350 x 350	300x500	400 x 400	300x500	450 x 450	300x500	500 x 500
2	300x500	300 x 300	300x500	400 x 400	300x500	450 x 450	300x500	500 x 500
3	250x500	300 x 300	300x500	350 x 350	300x500	400 x 400	300x500	450 x 450
4			300x500	350 x 350	300x500	400 x 400	300x500	450 x 450
5			300x500	300 x 300	300x500	350 x 350	300x500	400 x 400
6			250x500	300 x 300	300x500	350 x 350	300x500	400 x 400
7					300x500	300 x 300	300x500	350 x 350
8					250x500	300 x 300	300x500	350 x 350
9							300x500	300 x 300
10							250x500	300 x 300

To study the effect of initial deformation and cracks in the existing structure (prior to installation of steel braces) on the behavior of braced frames, staged analysis were performed on the braced frame models using the cracked section properties. The cracked moment of inertia used was 0.7 and 0.5 of gross moment of inertia for column and beam, respectively. The models were named BFnASC and BFnXSC. The S and C extension refer to staged analysis and crack section, respectively. For the staged analysis, staged construction analysis of SAP2000 was used in which the existing structure with full dead and live load was considered stage 1. Addition of steel braces was considered stage 2, and stage 3 was when the strengthened structure subjected with earthquake. The results from staged analysis was compared to those of conventional analysis in which, the strengthened structure was modeled as new and complete prior to the application of vertical and lateral loads.

To study the effect of additional braces on the performance of the structures, static push over analysis was done using the feature available in SAP2000. For the braces, initially W shape of 200x200x47.1 kg/m was used for all of the braces and then bigger sizes were used for the lower parts of 5, 8, and 10-story structures, to see the performance changes at first yield.

3. Results and discussion

3.1. Lateral deformation of open frames and braced frames

The lateral deformations of the existing and strengthened structures are shown in Fig. 3 for 3 and 5-story models and Fig. 4 for 8 and 10-story models. The graphs are plotted for loading combination of dead, live, and earthquake without any factor. It is apparent from the graphs that the models with additional braces (BFn) show much stiffer response than those of the bare frame models (OFn). The drift ratios of the open frame models are 0.20%, 0.23%, 0.20%, and 0.17% for 3, 5, 8, and 10-story structures, respectively. All of the numbers are within the maximum limit of 2% which means that the existing structures are very stiff to resist earthquake load. Comparison between manual calculation of static equivalent load and auto lateral loading feature of SAP200 (with AL extension) shows that the manual calculation is slightly more conservative.

The lateral deformations of the models with braces are much smaller than those of the bare frame models with ratios of 0.19, 0.29, 0.43, and 0.49 for 3, 5, 8, and 10-story models, respectively. Between the two brace type, the one with chevron "A" shaped braces (BF3A, BF5A, BF8A, and BF10A) are slightly stiffer than those with X-shaped braces (BF3X, BF5X, BF8X, and BF10X) with ratios of 1.05, 1.07, 1.05, and 1.04 for 3, 5, 8, and 10-story models, respectively.

Included in the graphs are deformations of braced frames resulted from staged analysis using cracked sections (dash lines with SC extension). Compared to the results from conventional analysis, staged analyses give significantly larger lateral deformations. The differences become more apparent as the number of story increases. For the 3 and 5 story models the difference are 8% and 10%, respectively. For the 8 and 10 story models the difference are 13% and 14%, respectively. Regardless of the magnitude of changes, for the case of retrofitting an existing structure, staged analysis using cracked section should be used as it will give more accurate and conservative results.

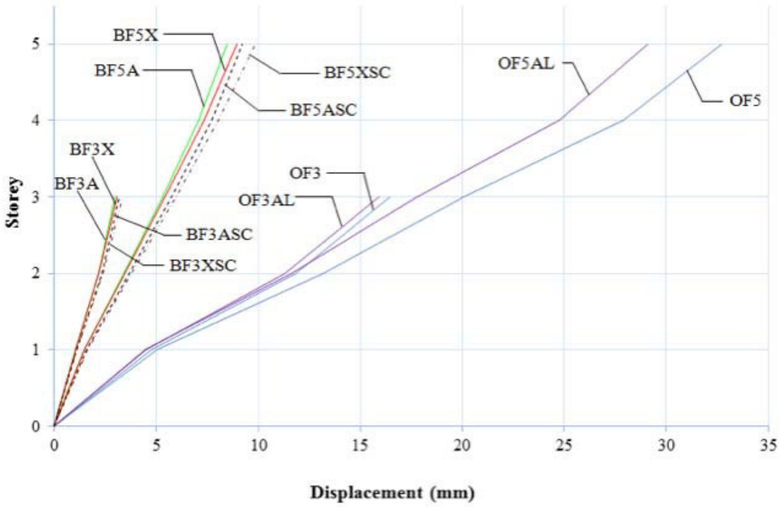

Fig. 3. Deformation of 3 and 5-story models of existing (OF) and strengthened structures (BF)

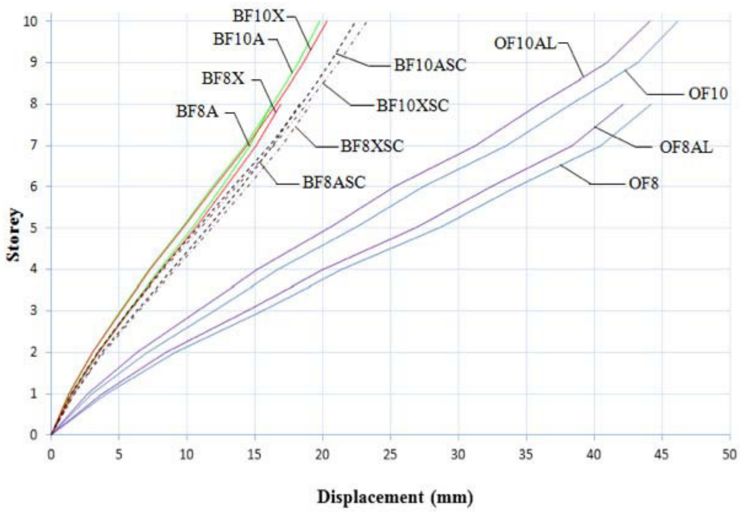

Fig. 4. Deformation of 8 and 10-story models of existing (OF) and strengthened structures (BF)

It is also apparent from Fig. 4 that the lateral deformation of 8-story structure is larger than that of the 10-story model. This is a special case in which the lateral loads due to earthquake for the same floor levels are bigger for the 8-story. It is also associated with the dimension of both frames.

3.2. Reinforcement requirement

The longitudinal reinforcement of the beam for the existing bare frame and braced frame models resulted from seismic design are shown in Table 2. The braced frame models require much less reinforcing steel than those of the open frame models, which means that the addition of steel braces reduce the internal forces in the frame element because the braces take some portion of the lateral loads. For the special case of chevron braces, the beam reinforcement at join where the two braces meet reduced by up to 600% when conventional analysis is used (BFA). Using staged analysis however (BFAS), the reduction is much lower. This means that the results from conventional analysis are far off. The result will be correct if the braces are installed when the existing RC frame has zero deformation.

Table 2. Longitudinal reinforcement of beams

Lvl.	OF				BFA				BFAS				BFX				BFXS			
	Negative		Positive		Negative		Positive		Negative		Positive		Negative		Positive		Negative		Positive	
3-3	296	339	213	333	142	276	36	302	206	249	151	232	284	334	207	302	221	261	161	232
3-2	321	375	198	319	124	244	31	290	208	235	165	228	263	313	197	286	208	245	165	228
3-1	347	425	207	358	109	248	27	298	207	240	167	237	260	317	197	293	207	245	167	237
5-5	225	212	166	245	161	232	46	223	193	212	145	182	270	294	182	227	213	230	153	182
5-3	388	419	251	373	131	306	65	297	228	279	182	234	313	391	219	288	246	294	188	234
5-1	435	459	255	409	43	280	51	291	192	259	171	228	241	358	201	283	192	264	171	230
8-8	208	155	195	241	155	226	87	268	210	216	171	189	276	286	220	258	228	233	182	199
8-4	441	419	299	375	74	325	114	348	227	295	199	243	297	408	242	312	240	306	206	248
8-1	459	459	287	391	62	298	95	290	177	278	176	233	226	377	205	285	177	282	176	236
10-10	190	138	209	236	129	198	97	278	217	215	188	204	254	255	233	265	202	202	179	296
10-5	445	379	311	349	51	302	134	369	235	297	211	266	283	387	249	328	224	288	205	260
10-1	459	459	290	362	68	292	118	287	181	282	178	230	241	359	205	276	182	279	177	229

Note: levl 5-3 means 3rd floor of 5-story model

The column reinforcement ratio of the existing bare frame was between 1 and 3 percent for all of the open frame models. For the strengthened models, the ratio becomes 1 percent, a minimum ratio allowed by the code [15]. Similar result was obtained for the shear reinforcement. The shear steel becomes minimum with the addition of steel braces.

3.3. Braces dimension and performance of the structures

Dimension of steel braces was determined considering the stresses in the braces. Initially, W shape of 200x200x47.1 kg/m was used for all of the models and the corresponding maximum stress ratio according to the Indonesian code of structural steel design [16] was 0.42 for chevron braces and 0.63 for X braces. Results from static pushover analysis shows that some braces yield before the RC frame element does. Then, a bigger brace was used for the lower part of the structures (250x250x68 for BF5, 300x300x88 for BF8, and 350x350x129 for BF10). The deformation and steel reinforcement requirement in the braced frame change slightly due to the change in brace dimension.

The pushover curves shows that the braced frames are stronger than the open frames. Data from the first yield of all models are used to compare the performance of each model. Table 3 shows the results from pushover analysis.

Index 1 of BFA and BFX refer to bigger size braces. It is clear from the table that using bigger size braces, the first yield of 3 and 5-story models occurred at larger base shear and smaller lateral displacement. It means that the structure becomes stronger and stiffer when bigger braces were used. This is also true for the 10-story models except that the base shear at first yield remain the same when bigger braces were used. For the 8-story models however, the first yield occurred at the same displacement and lower base shear when bigger braces were used.

Table 3. Displacement D (mm) and base shear V (kN) from pushover analysis

Model	3-Story		5-Story		8-Story		10-Story	
	D	V	D	V	D	V	D	V
OF	57	2569	80	2989	140	4654	105	3245
BFA	16	4023	27	3978	44	4692	44	3902
BFX	22	5400	25	3574	38	3833	45	3745
BFA1	11	2850	26	4489	44	4692	44	3902
BFX1	22	5400	24	3855	38	3833	45	3745

3.4. Dynamic properties of the structures

The consequence of modifying flexible structure to become stiffer one is that their dynamic properties will also change. In this case the natural periods become smaller. Table 4 shows the periods of each model using smaller size braces (T1) and bigger braces (T2). It is apparent from the table that the period of the structure reduces significantly when braces were added. Using bigger braces also reduce the natural period of the structure.

Table 4. Natural period of the models (sec.)

Model	OF3	BF3A	BF3X	OF5	BF5A	BF5X	OF8	BF8A	BF8X	OF10	BF10A	BF10X
T1	0.730	0.312	0.318	1.018	0.528	0.542	1.369	0.907	0.885	1.566	1.083	1.099
T2	-	-	-		0.496	0.517		0.797	0.828		0.987	1.021

3.5. Significance of staged analysis for retrofitted structures

Staged analysis is a complex set of analysis procedure that starts from non-zero deformation suitable for the case of adding new component to an existing structure that already deformed and probably cracked. Compared to the conventional analysis in which all component of the structure are considered to act at the same time, the staged analysis will give larger deformation and internal forces that correspond to larger stresses. Accordingly, staged analysis should be used in case of retrofitted structures. Performances of the retrofitted structures also need to be checked to ensure that the structures will fail in a more ductile manner because the stiffened structures will results in smaller natural period which correspond to larger seismic demands.

4. Conclusion

The RC open frame structure retrofitted with steel braces of chevron A and X-shaped showed significantly smaller lateral deformation under seismic loading combination. The steel reinforcement requirement also reduced significantly as a result of smaller internal forces in the frame members. The strengthening techniques worked well for low and medium-rise buildings. Interestingly enough, the braced frame of chevron A type showed better behavior and performance than those using X-shaped braces. Compared to the results from conventional analyses, staged analysis using cracked section increased the lateral deformation of the braced frame structure by up to 10%

for low-rise and 14% for medium-rise. The dimension of braces should be designed considering not only the stresses of the braces but also the performance of the braced structure.

References

[1] BSN, Standar Perencanaan Ketahanan Gempa Untuk Struktur Bangunan Gedung SNI 1726:2002. Badan Standarisasi Nasional, Jakarta, 2002

[2] BSN, Perencanaan Ketahanan Gempa Untuk Struktur Bangunan Gedung dan Non Gedung SNI 1726:2012. Badan Standarisasi, Nasional, Jakarta, 2012

[3] FEMA, Techniques for the Seismic Rehabilitation for Existing Building FEMA 547, Federal Emergency Management Agency, 2006

[4] M. Rodriguez, R. Park, Repair and Strengthening of Reinforced Concrete Buildings for Seismic Resistance, Earthquake Spectra Vol. 7 No. 3, 1991

[5] T. Fukuda and H. Ito, Past Earthquake Disasters; Examples of Earthquake Damage to Building Structures; Seismic Retrofit of Buildings, The Training Program on Steel Construction for Indonesia, Japan, 2015

[6] M. Sukrawa, I.B.D. Giri, Analisis Konstruksi Bertahap Pada Struktur Rangka Terbuka Beton Bertulang Dengan Perkuatan Breising Baja, 2015

[7] M.R. Maheri, Internal Steel Bracing of RC Frames, 3rd International Conference on Concrete & Development, Tehran, Iran, 2009

[8] A. Massumi, A. Absalan, Interaction Between Bracing System and Moment Resisting Frame in Braced Frame, Archives of Civil and Mechanical Engineering, Vol. 13, 260-268, 2013

[9] M.A. Youssef, H. Ghaffarzadeh, M. Nehdi, Seismic Performance of RC frames with Concentric Internal Steel Bracing, Engineering Structure Vol. 29, 1561-1568, 2007

[10] Ismail et.al, Analisa Perkuatan (Retrofitting) Gedung STKIP ADZKIA Padang dengan Menggunakan Bresing Baja, Prosiding Seminar Nasional Teknik Sipil 1 (SeNaTS), Sanur-Bali, 2015

[11] A. Massumi, A.A. Tasnimi, Strengthening of Low Ductile Reinforced Concrete Frames Using Steel X-Bracing with Different Details, Proceedings of the Fourteen World Conference on Earthquake Engineering (14WCEE), Beijing, China, 2008

[12] Computers and Structures Inc., CSI Analysis Reference Manuals, 1995 University Avenue Berkeley,

[13] K M Pathan, S.W. Ali, M. Waseem, H.T. Khan, S. Zubair, Construction Stage Analysis of RCC Frames, International Journal of Engineering & Technology Research Volume-2, Issue-3, May-June, 2014 pp. 54-58, 2014

[14] ACI, Building Code Requirements for Structural Concrete ACI 318M-11, American Concrete Institute, 2011

[15] BSN, Persyaratan beton struktural untuk bangunan gedung SNI 2847:2013, Badan Standarisasi Nasional, Jakarta, 2013

[16] BSN, Spesifikasi untuk bangunan gedung baja structural, SNI 1729:2015, Badan Standarisasi Nasional, Jakarta, 2015